Analysis of Lighting Fixtures

MMR Project No. 82999

Contract No. 62389

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REPORT TO:

MassDOT

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Contract No. 62389

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From
Massachusetts Materials Research, Inc.

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1. BACKGROUND

On March 16, 2011, Massachusetts Materials Research, Inc. (MMR) was requested by MassDOT to perform an evaluation of the light fixtures from the Thomas P. "Tip" O'Neill Tunnel.

A failed light fixture wireway and base were submitted to MMR for analysis and determination of the root cause(s) of the failure.

A new assembled light fixture and two new wireways manufactured by two different companies were also submitted to facilitate the analysis.

The dates of the submitted samples and description together with MMR identification is shown in Table I below.

Table I
Sample ID and Description

MMR ID	Sample Description	Date Received
Sample #1	A failed wireway removed from MHS Tunnel Roadways with evidence of corrosion, date 02/08/2011. This wireway was manufactured by NuArt Lighting.	03/17/2011
Sample #2	A new wireway, manufactured by NuArt Lighting.	03/17/2011
Sample #3	A new wireway, manufactured by Schreader.	03/17/2011
Sample #4	An assembled new light fixture. This assembled fixture did not contain any wireway.	03/17/2011
Sample #5	The light fixture base of sample #1. This piece contained three stainless steel clips which would be attached to the wireway interface in service.	03/21/2011

2. INVESTIGATION

In-detail visual examination and photographic documentation were performed on the failed and new samples.

Representative smaller segments were excised from the longer wireway pieces to facilitate further in-detail analysis. Overall examination of the wireway clearly revealed that the lip areas of the wireway where the light fixture was attached with clips were completely consumed by corrosion which allowed the attached light fixture to separate from the wireway attached to the tunnel ceiling and fall apart.

Representative sections from two of these completely consumed areas, areas next to them, areas away from them with less corrosion, and similar areas from the two new samples were excised into smaller pieces, encased in plastic, ground and polished, to facilitate optical microscope examination. The prepared cross-sections are called metallurgical "mounts". The mounts were examined both in the unetched and etched conditions. In the unetched condition, overall

corrosion, depth of corrosion, surface condition, inclusions, etc. are evaluated. In the etched condition, the corrosion propagation path, grains and other microstructural features are developed and evaluated.

Tensile testing was performed on sample #1 (failed, NuArt), sample #2 (new, NuArt) and sample #3 (new, Schreader). Chemical analysis was performed on sample #s 1 and 3 for material identification.

One of the clips from the new light assembly was analyzed chemically.

A clip from the failed assembly was evaluated for corrosion. A mount was prepared to determine any evidence of corrosion and any microstructural anomalies.

The new wireways were examined for coating integrity and coverage. Any handling related anomalies were also noted.

The white powder coating for sample #s 2 and 3 were analyzed by Fourier transform infrared (FTIR) spectroscopy. FTIR is a chemical analysis technique to identify the polymers. The characteristic infrared (IR) bands are "fingerprints" of the functional groups that make up the polymers and identify their chemical compositions. This analysis would also identify any curing issues associated with the powder coatings.

Adhesion testing for the coating adherence to the substrate was performed following the guidelines of ASTM D3359-09 Specification, Method A. Sample #s 2 and 3 were tested for adhesion.

Two mounted cross-sections from sample #s 2 and 3 were examined at higher magnifications in the scanning electron microscope (SEM) to determine the presence of any anodized layer on the wireway. Since the optical microscope examination was not conclusive about the presence/absence of the anodized layer, the mount needed to be examined at a higher magnification. Energy dispersive x-ray spectroscopy (EDS) was performed on the mounted cross-section to determine the presence of the anodized layer. EDS is a semi-quantitative microchemical analysis technique performed using equipment attached to the scanning electron microscope (SEM). This is an elemental analysis technique. The analyses were performed both in the standard and in the "Light Element" (LE) modes. Note that the LE mode is more sensitive to the elements with lower atomic weights (e.g. carbon, oxygen). The graphs obtained from the EDS analysis are called "spectrograms". The peak heights of each element on the graph indicate the relative amounts of the elements present in the particular area analyzed. The elements are reported qualitatively as major, minor and trace amounts.

The different colored deposits noted on the failed wireway were collected and analyzed by EDS. This would provide information about the aggressive elements in the corrosion deposit and hence the compound(s) causing the corrosion.

3. RESULTS

3.1 Visual Examination

Overall review of the assembled light fixture showed that the lighting portion is attached to an aluminum base. This aluminum base is attached to the wireway which is secured on the tunnel ceiling. The base of the aluminum fixture contains five retention clips on each side; the clips appeared to be of stainless steel (SS) type. The clips are screwed onto the aluminum base of the fixture. It appears that the entire light fixture is assembled first and then clipped on to the wireway with the retention clips. The clips attach to a lip type area of the wireway. The overall weight of the light fixture (reported to be 110 lbs) is distributed among 10 clips attached to the wireway.

The failed wireway showed complete consumption of material at the lip locations where the clips were attached. All ten locations of the wireway revealed complete consumption of the lip width. This indicated that for this particular fixture, corrosion of the lip areas, where the clips were attached, initiated and propagated at about the same rate. The light fixture disengaged or fell apart from the wireway when the material at the mentioned locations was consumed.

The wireway displayed separation of the white coating from the surface almost everywhere. The aluminum surface at the lip and adjacent areas revealed complete removal of the coating. These areas also showed shallow surface corrosion; numerous yellowish/whitish deposits were noted all over the exposed aluminum surface. In some locations, some grayish type debris was also noted which appeared to be aluminum corrosion byproduct. The side surfaces of the wireway revealed dark color deposit on top of the white coat which was separated from the aluminum substrate. This surface was exposed to the environment and, most likely, the dark deposit was from the sulfur exhaust from the vehicles.

All different colored debris was collected and later analyzed by EDS. Some of the debris was also collected to determine the pH of the solution.

The base of the light fixture which was attached to the wireway revealed corrosion at the locations where the clips were screwed on. However, the corrosion did not appear to be as significant as the wireway engagement locations. Away from the screwed on clip locations, peeling off of the coating was noted from the substrate with whitish/yellowish debris on the aluminum substrate. The areas away from the clips did not reveal any evidence of significant corrosion of the aluminum base.

Representative photographs from the incident/failed wireway are presented in Figures 1 – 8.

Representative views from the failed base are presented in Figures 9 – 14.

The two new wireways were also examined for overall coating coverage and integrity viewpoints. Some of the isolated locations revealed breaching of coating due to mechanical damage which was created in different handling steps. There are some isolated areas that

displayed absence of coating from the coating application process. Breaching of coating was noted at the screwed on grounding lug locations. This condition indicates that during the screw installation operation the coating can be breached easily.

Representative views from the new wireway samples are presented in Figures 15 – 20.

3.2 Chemical Analysis

Chemical analysis was performed on sample #1 (failed, NuArt) and sample #3 (new, Schreader). Both wireway materials were identified to be aluminum alloy 6063 (Al 6063). The chemical analysis results are shown below in Table II.

Table II
Wireways: Chemical Analysis Results

Element	Compositional (wt. %)		
	Sample #1	Sample #3	UNS A96063
Aluminum	Remainder	Remainder	Remainder
Chromium	0.02	0.03	0.10 max.
Copper	0.02	0.06	0.10 max.
Iron	0.23	0.20	0.35 max.
Magnesium	0.51	0.48	0.45 – 0.90
Manganese	0.02	0.04	0.10 max.
Silicon	0.42	0.43	0.20 – 0.60
Titanium	0.01	0.01	0.10 max.
Zinc	0.02	0.02	0.10 max.
Other (Each)	<0.05	<0.05	0.05 max.
Other (Total)	<0.1	<0.1	0.15 max.

A new clip from the light assembly was analyzed and was identified to be similar to UNS S30400 (304 SS) material. The chemical analysis results are shown below in Table III. The table also shows the compositional requirements for 316 SS and 304 SS material. Note that the clip is similar to 304 SS but does not meet the requirements.

Table III
Clip: Chemical Analysis Results

Element	Composition (wt. %)		
	Clip	UNS S31600	UNS S30400
Carbon	0.071	0.08 max.	0.08 max.
Chromium	17.74*	16.00 – 18.00	18.00 – 20.00
Manganese	1.27	2.00 max.	2.00 max.
Molybdenum	0.42**	2.00 – 3.00	----
Nickel	8.20**	10.00 – 14.00	8.00 – 10.5
Phosphorous	0.03	0.045 max.	0.045
Sulfur	.001	0.030 max.	0.030
Silicon	0.55	1.00 max.	1.00

Note: *Does not meet specification requirements for UNS S30400
**Does not meet specification requirements for UNS S31600

3.3 Tensile Test

Tensile testing was performed on sample #s 1, 2 and 3. The test specimens were obtained from the flat portion of the wireways. Table IV below shows the tensile test results. The table also includes the published values for Al 6063 -T5 and -T52 tempers.

Table IV
Tensile Test Results

Sample	Ultimate Tensile Strength (ksi)	.2% Yield Strength (ksi)	Elongation (%)
1	34	31	11
2	37	34	9
3	37	34	9
Al 6063-T5	22 minimum	16 minimum	8 minimum
Al-6063-T52	22-30	16-25	8 minimum

The tensile results identify the Al 6063 material to be in T5 temper condition.

The UTS and .2% YS values for all three samples are higher than the allowed maximum for the T52 temper condition for Al 6063 material.

3.4 Coating Analysis

3.4.1 Adhesion Test per ASTM D3359-09

Adhesion testing of the white coating to the substrate was performed according to the ASTM specification ASTM D3359-09, Method A. In this method, an "X" is cut on the coating and then a pressure sensitive special tape is applied on the X marked area and peeled off. When no coating is removed on the tape from the substrate, the rating is 5A according to the ASTM Specification.

Both sample #s 2 and 3 were rated as 5A.

3.4.2 Chemical Analysis

FTIR analysis performed on the coatings for sample #s 2 and 3 identified them to be similar to a polyester base powder coating. The color pigmentation was identified to be predominantly titanium oxide by EDS analysis. No anomalies were detected in the coating samples.

3.5 Metallurgical Analysis

The locations of the mounts are shown in Figures 21 – 25 for sample #s 1, 2 and 3.

Sample #1 (Failed, NuArt): Transverse cross-sections form severely corroded areas at two wasted locations, areas adjacent to these, and representative areas away from the severe corrosion were prepared. The mounts contain the failure location and the areas adjacent to the failed lip.

Examination of the mounts revealed significant corrosion of the wireway at the locations where the light fixture was attached to the 300-series stainless steel (SS) clips. The complete thickness of the wireway lip was consumed at these engagement locations resulting in separation of the light fixture from the wireway. Corrosion was also noted on areas adjacent to the failed lip location, but to a lesser degree.

The cross-section away from the severely corroded areas showed initiation of corrosion in an intergranular mode, which progressed to a more pitting type general corrosion. Note that corrosion to a significant depth was not noted for the areas away from the engagement locations.

No anodized layer appeared to be present on the mounts evaluated.

Representative overall stereomicroscopic views from different mounted locations are presented in Figures 26 – 35. Note that Mount 1-3, which is away from the clip engagement location, displayed only isolated areas of shallow corrosion at the lip area. Maximum depth of corrosion at this location was measured to be 0.003" for this mount.

Optical microscope views for Mounts 1-3 and 1-2(at a distressed location) are presented in Figures 36-46.

Sample #s 2 and 3-New: The metallurgical structure of the wireway samples revealed heat treated grains with precipitation which is expected for an Al 6063 material in -T5 temper condition.

Adhesion of the coating to the substrate appeared to be satisfactory for both samples; no significant contamination was noted at the interfaces.

Representative views showing non-uniform coating distribution and interface condition are presented in Figures 47-56.

Optical microscope examination did not reveal any detectable anodized layer. The mounts were examined at higher magnifications in the SEM and analyzed by EDS for confirmation.

There was no presence of any anodized layer on the new wireway samples examined.

Coating thickness: Coating thickness varied significantly on the lip and adjacent areas. Special attention was paid to the lip area as this area revealed failure by corrosion. The coating appeared to be significantly thin at the edge of the lip. Note that typically for a spray powder coat, the edges/corners are prone to have thinner coating application. This is inherent to the coating process. Some of the radii areas revealed thicker deposition with many flat areas displaying variable coating thickness.

For sample #2 (NuArt), the typical coating thickness at the lip edge was 0.0005" and on other areas predominantly 0.002". Note that in many locations, the coating was significantly thicker also.

For sample #3 (Schreader), the coating thickness at the root edge was 0.0007" and on other areas predominantly 0.0024". This sample also revealed thicker coating deposition in many areas.

Representative stereomicroscopic views are displayed in Figures 57 – 68.

Failed Clip: A mount was prepared through one of the failed clips at the location which is attached to the wireway. No corrosion was noted on the clip at the engagement or any other areas. The microstructure was typical for a 300-series SS and was acceptable with austenitic grains and no anomalies.

Representative optical microscope views from the mounted cross section at the edge and inner bend of the engagement location to the wireway are shown in Figures 69-75. Higher magnification views did not show any corrosion.

No protective coating was noted on the stainless steel clip.

3.6 Deposit Analysis

The different colored deposit/debris samples collected from the failed wireway were analyzed by EDS. Table V below shows the qualitative EDS analysis results.

Table V
EDS Analysis Results

Deposit sample	Composition (wt. %)		
	Major	Minor	Trace
Yellow/White Colored (from lip area)	Oxygen, Aluminum	Chlorine	Sulfur, Sodium
Grey Colored (from lip area)	Oxygen, Aluminum	Chlorine, Sodium	Sulfur, Calcium
Dark (from side surfaces on top of the coating)	Oxygen, Silicon, Sulfur, Chlorine	Calcium, Sodium, Aluminum	Carbon, Potassium, Calcium, Iron

The deposit analysis results clearly indicate aluminum oxide corrosion byproducts. The aggressive species is identified to be chloride ions from the environment the source of which is, most likely, road salt (sodium chloride) and/or the ocean.

Representative EDS spectrograms are displayed in Figures 76-78.

The pH of the deposit solution was measured to be 4.7 which is acidic.

Note that water has a neutral pH of 7.0. A number higher than 7.0 indicates a basic solution and the number lower than 7 indicates an acidic solution.

4. DISCUSSION

Aluminum alloy Al 6063 in the extruded heat treated condition (either T5 or T52 temper) appears to be an acceptable aluminum material selection for the wireway and light fixture base/frame components. This material is known to have good general corrosion resistance and a significant resistance to stress corrosion cracking (SCC). However, in an aggressive environment, this material, as well as any other aluminum material, will show corrosion.

The white powder coat was applied on the light fixture aluminum metallic components, we believe, to provide corrosion resistance to the material by providing a barrier with the environment and the aluminum material. When the coating is breached, due to handling or assembly, the base aluminum material will be exposed to the environment. If the environment is aggressive, the base material will experience corrosion.

The powder coat applied on the aluminum wireway and frame is not hard and can be easily damaged. Especially at the corner/edge locations, the coating can be thin and can be easily breached.

We believe that during the assembly of the clip to the wireways, the coating at the edge of the lips was breached. This condition exposed the aluminum base material to the tunnel environment. Due to the presence of the clip at the engagement location, a tight crevice is created. The chloride ion containing aggressive species would initiate corrosion of the aluminum base material initially in the intergranular form which would progress to pitting and general corrosion eventually. The crevice with the assembly stress would increase the corrosion rate. Eventually when the two dissimilar materials, the Al 6063 and 304 SS, are in contact with the chloride containing electrolyte, a galvanic cell would be created. In this situation, the more active aluminum material would corrode at a faster rate and the aluminum substrate will be completely consumed.

The clip we have examined did not show any corrosion. However, we have noticed some rust colored deposit on the failed large fixture base. This would indicate that some of the clips may have shown some corrosion. It is not the requirement in a crevice corrosion situation that the 300 series SS clips will have to corrode. It may or may not show evidence of corrosion depending on whether it is anodic or cathodic to its mated material.

When two dissimilar metals are placed in a conductive/corrosive solution, there will be a potential difference between the two. This will cause flow of electrons (electricity) between them when they are connected and hence corrosion of the mated metals. Because of the dissimilar metals and flow of electric currents, the form of the corrosion is called Galvanic or Dissimilar Metal/Two-Metal corrosion. In the mated pair, the less corrosion resistant material (anode) will show increased corrosion and the more resistant material (cathode) will show decreased or no corrosion.

Figure 79 shows a Galvanic Series for some commercial metals in seawater.

The further apart the paired materials are in the galvanic series, the higher will be the potential difference between them and more corrosion of the anodic component.

The mated pair in the subject failure is the stainless steel (passive, as the clips were generally uncorroded) clip and the aluminum wireway. The aluminum is the more anodic component and would corrode at a much faster rate when the two metals are connected in the presence of a moist aggressive environment.

The overall morphology of the failed areas indicates that the primary cause of the corrosion is the breaching of the protective white coating layer which allowed initiation of crevice corrosion. Galvanic corrosion is a secondary contributory factor.

Some corrosion has been noted on areas away from the engagement locations. The corrosion on these areas did not appear to have significant depth and was generally contained on the surface.

When the coating layer is disturbed, the aggressive environment will attack the aluminum base material and initiate corrosion.

At the engagement locations, a combination of a crevice, high assembly stress and dissimilar metals, all contributed to the corrosion related failure of the light fixture.

The new light fixture was assembled to the new wireway pieces, sample #2 (NuArt) and sample #3 (Schreader). The clips were attached with extreme care. It was noted that for both samples, the coating was abraded at the lip edge locations; the damage was greater for the NuArt sample than compared to the Schreader. Effort was needed to assemble the wireway to the light on the NuArt sample. The Schreader wireway assembled easily

Representative views of coating damage on the new wireways from the clip assembly process are presented in Figures 80-88.

5. CONCLUSIONS

The subject light fixture failed due to severe corrosion of the aluminum wireway at the locations where the light assembly was attached to the wireway with stainless steel clips. The aluminum material at these clip locations revealed significant corrosion and complete consumption of the material at these lips, which allowed the heavy light fixture to fall apart from the wireway base. Note that the length of the light fixture is about 6 feet and is attached to the wireway with five clips on each side.

The aggressive species which caused the severe corrosion is the chloride environment.

Corrosion was most severe at the clipped locations due to the creation of a tight crevice at the joints. The presence of two dissimilar metals, namely, aluminum 6063 and 304 SS, would create a galvanic cell. Aluminum material is significantly active and would corrode at an accelerated manner with respect to 304 SS material. Note that galvanic corrosion played a secondary role in this failure. The primary cause is the corrosion of aluminum wireway materials at a tight crevice due to the presence of aggressive environment at breached coating locations.

The clips appear to be significantly tight at the joint locations. The aluminum wireway revealed a significantly thin layer of coating on the lip edges. This is typical of powder coated materials and is inherent to the coating process. The stainless steel tight clips during assembly could have breached the thin layer of coating. The coating can also be breached by mechanical damage during handling. The absence of the coating would expose the aluminum base material to the harsh environment and would initiate corrosion. Note that corrosion is higher at crevices and is accelerated under stress.

The general corrosion resistance for the aluminum 6063 material is satisfactory. However, it is known to show corrosion in aggressive environment which is typical of multiple alloy systems.

The overall general corrosion noted on the aluminum wireway and fixture base was not too severe and is not expected to cause a light fixture separation/failure in a reasonable length of time. If the crevices and dissimilar metal contacts can be avoided in the assembly, the corrosion rate of the wireways would slow down significantly.

5.1 Estimated Service Life of the Light Fixtures

We assume that many of the wireways in the tunnel exhibit corrosion at the retention clip engagement locations, including separation of the powder coat from the aluminum wireway/base substrates. In our analysis we have noted shallow surface corrosion on the wireway lip areas away from the engagement locations for the failed wireway. Some corrosion was also noted on the aluminum base where the retention clips are screwed on.

We suggest removing the retention clips from the present locations to other areas of the lip where only surface corrosion is noted. Even in the absence of the powder coat, it should take about 3 to 4 years for the wireway lip thickness to be completely consumed based on the corrosion noted at the engagement locations of the failed wireway. Note that the subject failed wireway was in service for about 8 years. This assumption should be valid if the light fixtures experience the same environmental conditions as the failed one.

We would also strongly recommend checking the engagement locations for corrosion periodically, for instance, every six months. Both the wireway and light base should be examined for corrosion. If material wastage is noted during this examination, moving the clips again is recommended.

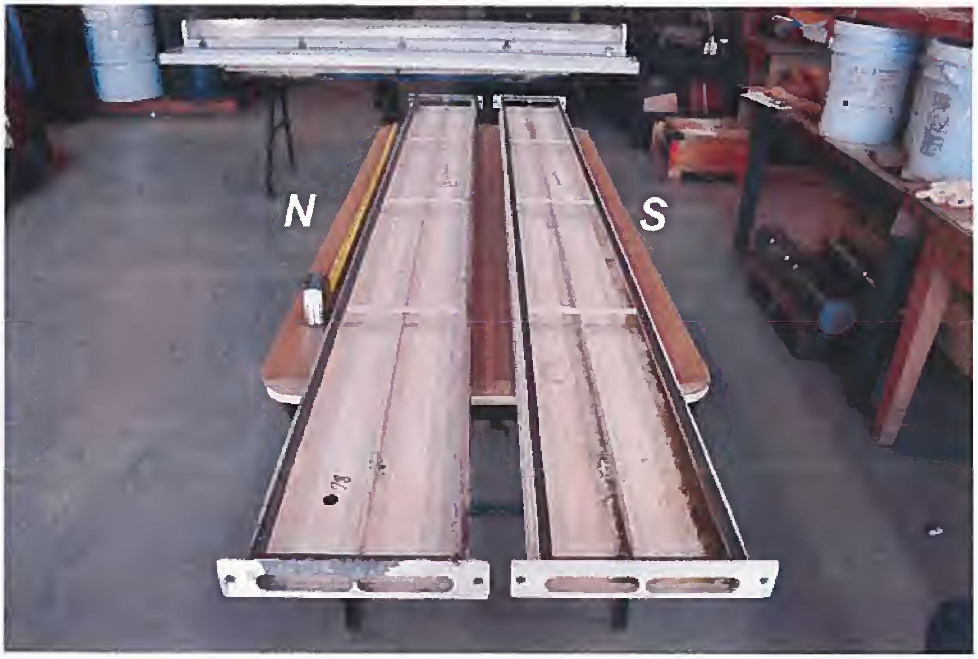


Figure 1: Incident wireway (N) and Schreader comparitor (S) as-received with exemplar light assembly in background.

Figure 2: Incident wireway label. Note corrosion and lack of white coating on sides.

Figure 3: Corrosion was present under the white coating at the gasket.

Figure 4: Wasted wireway metal at a former clip location, red arrow. Corrosion debris, blue arrows, was present wherever coating could be removed.

Figure 5: Another clip location, arrow.

Figure 6: Detail of Figure 5 clip location. Also note soot-blackened paint surface on side rails.

Figure 7: Incident wireway end cap, overall.

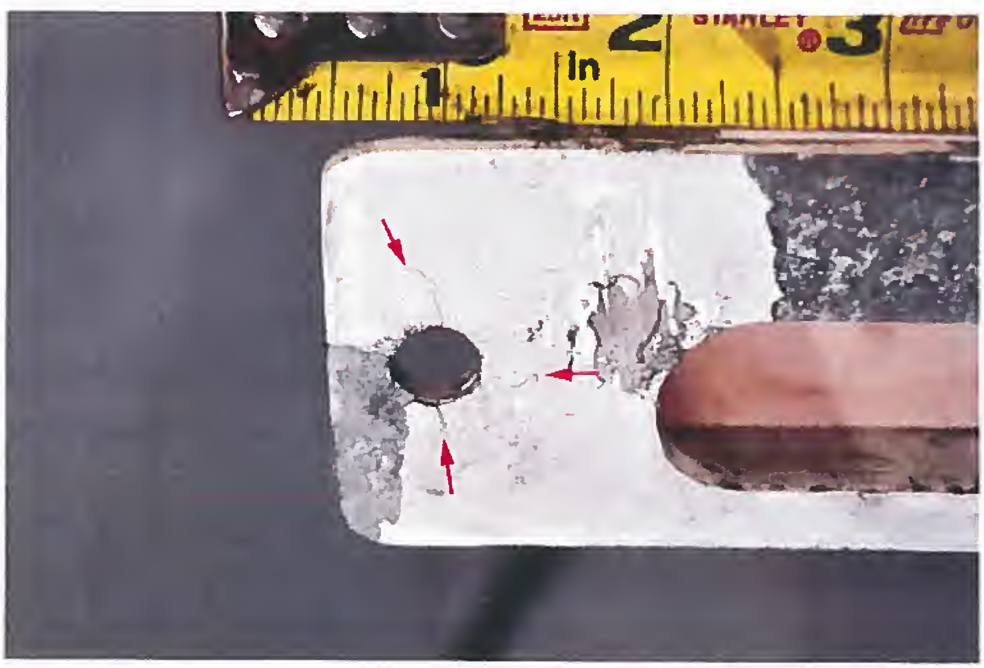


Figure 8: Incident wireway end cap at screw hole; note paint cracks emanating from hole, arrows, and lack of paint in hole.

Figure 9: Base from light that fell onto the roadway, one side, as-received.

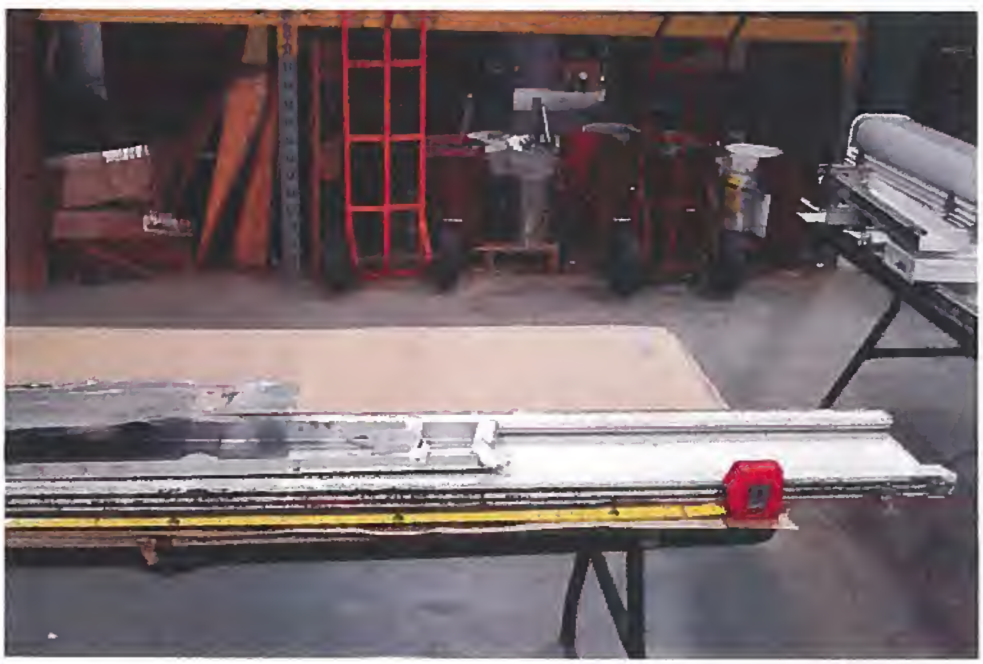


Figure 10: Base from light that fell onto the roadway, other side, as-received.

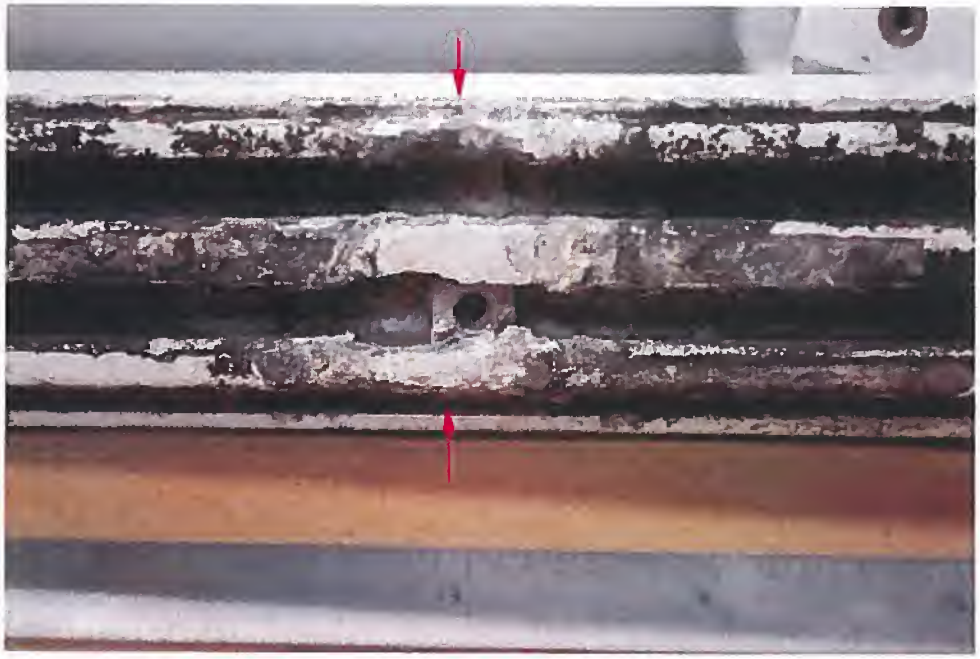


Figure 11: Clip locations on the incident light base also exhibited metal wastage, arrows.

Figure 12: Isolated rust-colored regions were present at clip locations on the incident light base, arrow, but they were rare.

Figure 13: A typical clip from the incident base.

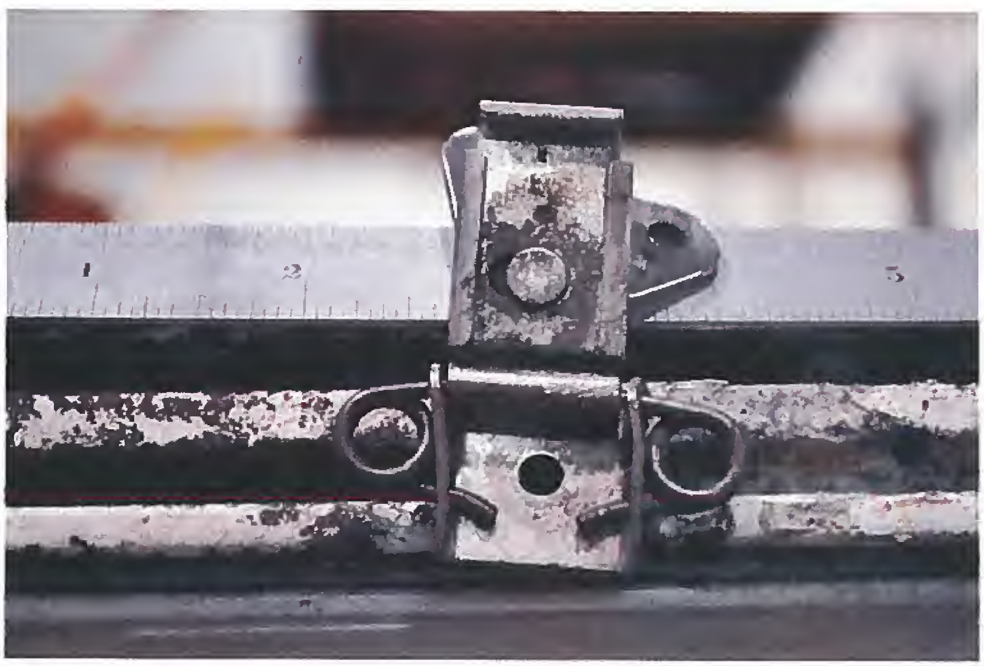


Figure 14: Typical clip underside from the incident base.

Figure 15: Unused Schreader wireway handling damage to white coating, as-received, arrows.

Figure 16: The end caps and most edges of the unused Schreader wireway exhibited mechanical damage to the coating, arrows.

Figure 17: Typical edge damage to coating on both unused wireways, arrows.

Figure 18: The unused NuArt wireway exhibited mechanical damage similar to the Schreader, arrows.

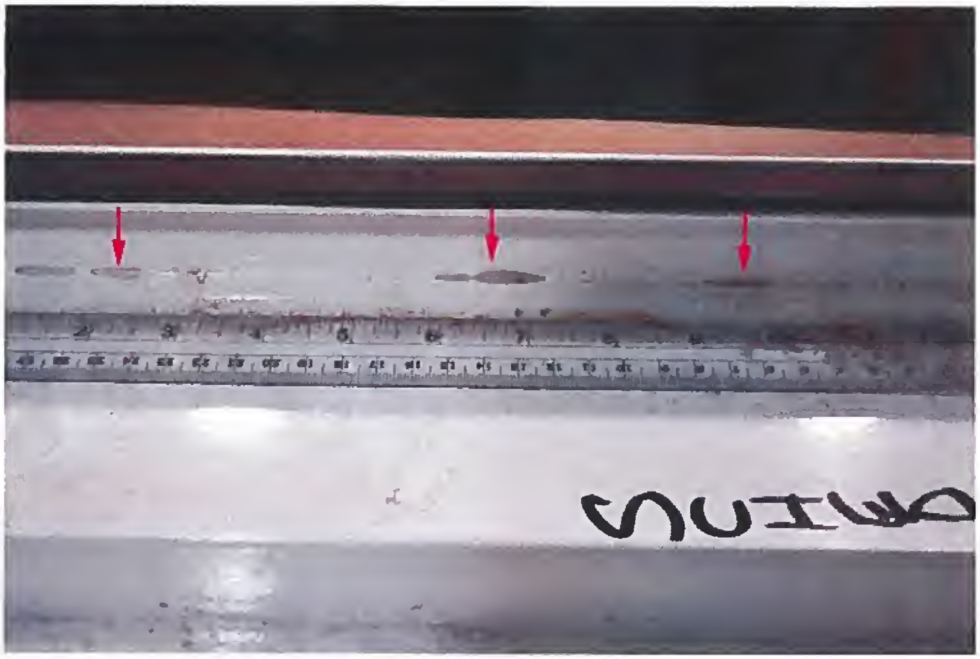


Figure 19: The unused Schreader wireway possessed large gaps in its coating at an interior recess, arrows.

Figure 20: Unused Schreader wireway: grounding lug at an interior surface. Note the breached coating, arrows, during installation of the screws.

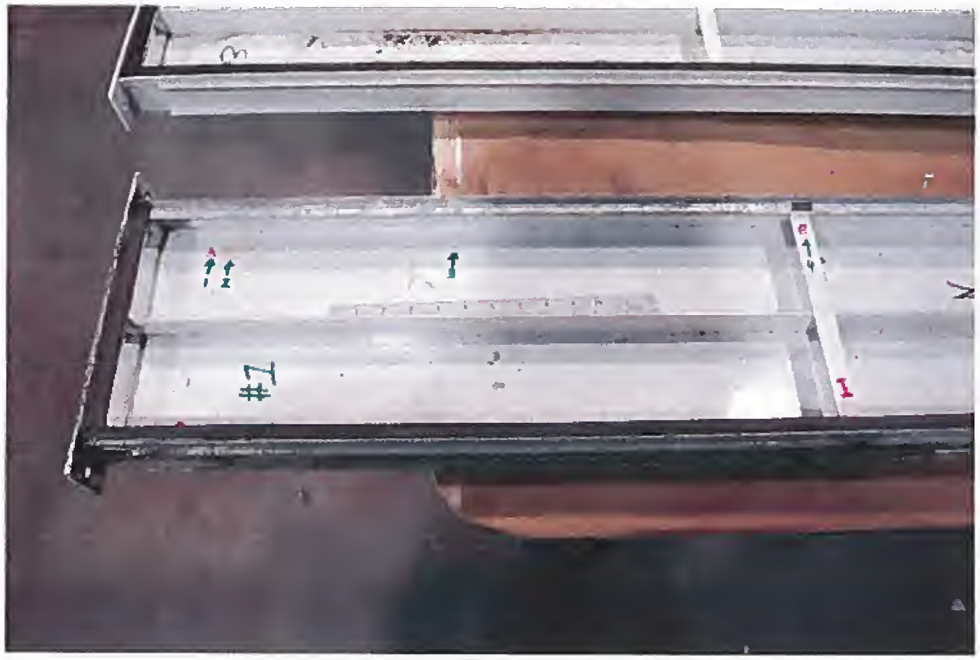


Figure 21: Sample #1: Overall locations for mounted transverse cross-sections 1 – 5 through two wasted locations and one location (#3) in-between them.

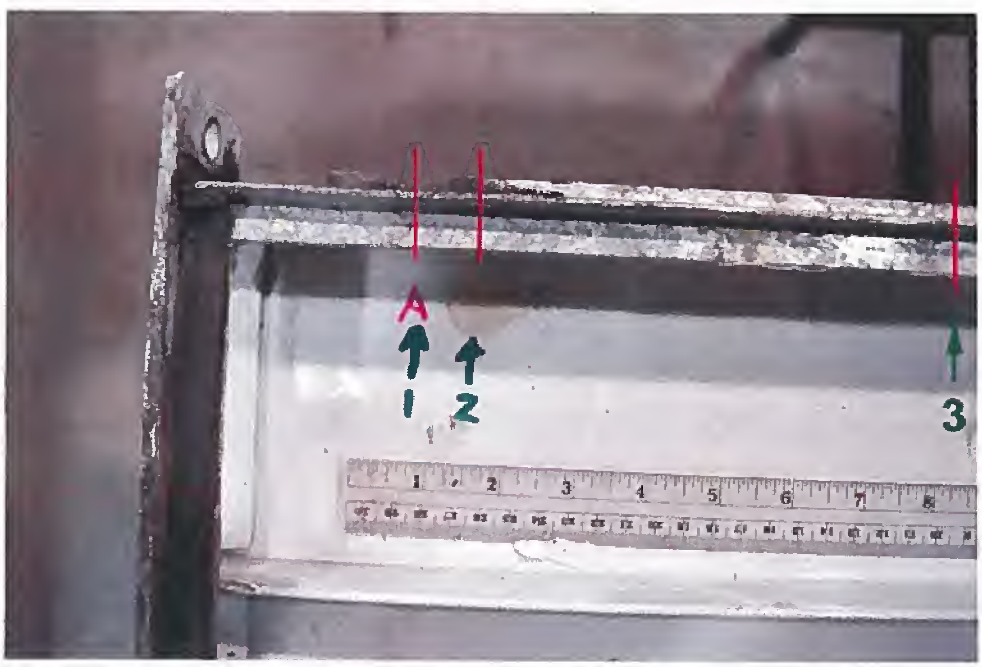


Figure 22: Sample #1: A close-up view for cross-sections 1-1, 1-2 through one of the distressed locations and one cross-section 1-3 through an area away. Note that all the cross-sections were transverse including the lip and adjacent areas.

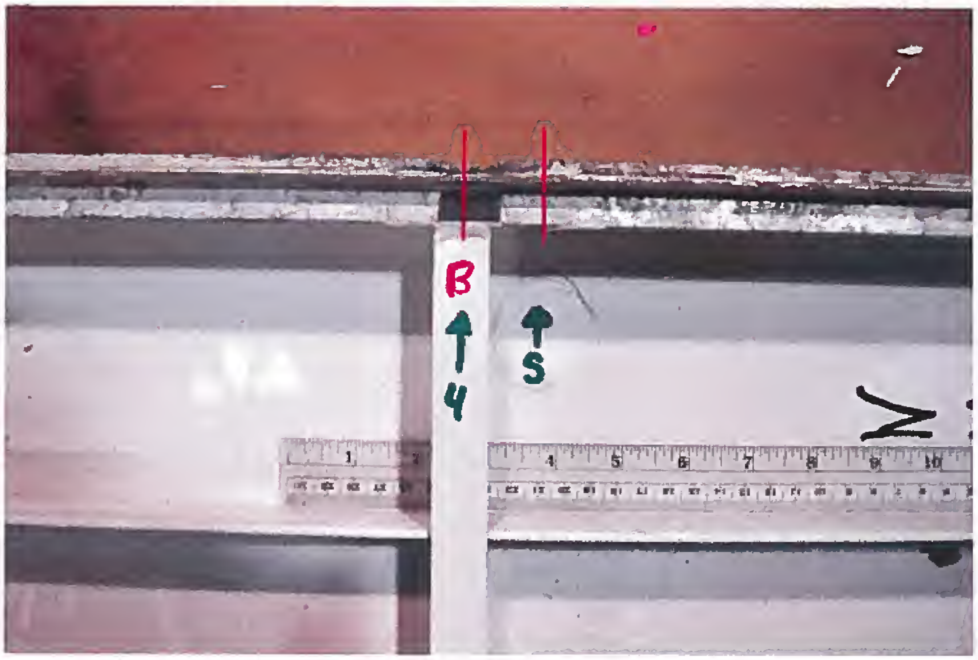


Figure 23: Sample #1: A close-up view of cross-sections 1-4 and 1-5 through a second completely wasted location.

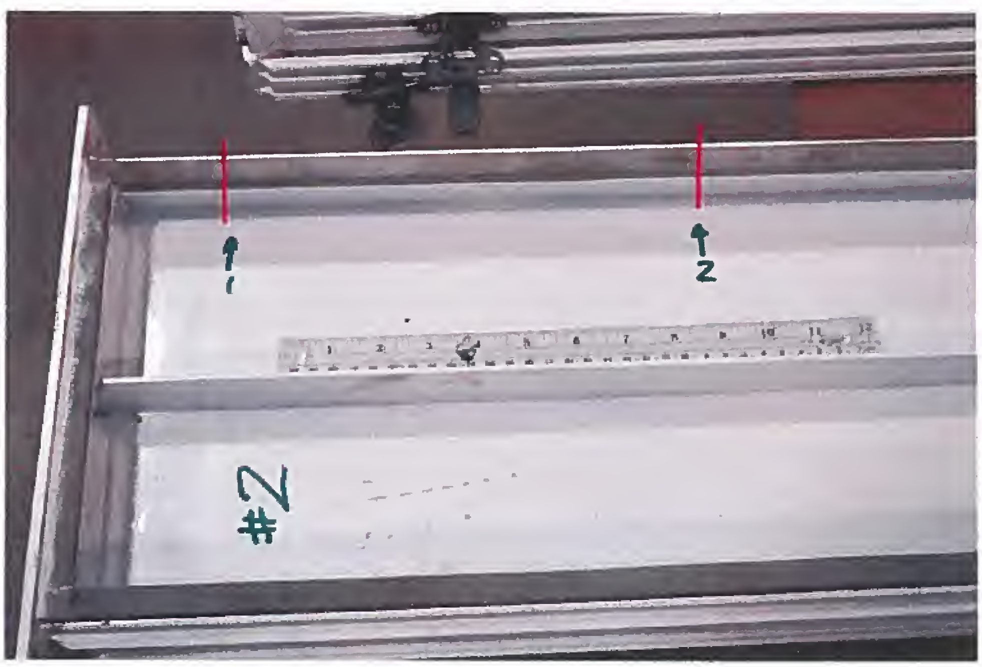


Figure 24: Sample #2: The transverse cross-section location for 2-1 and 2-2.

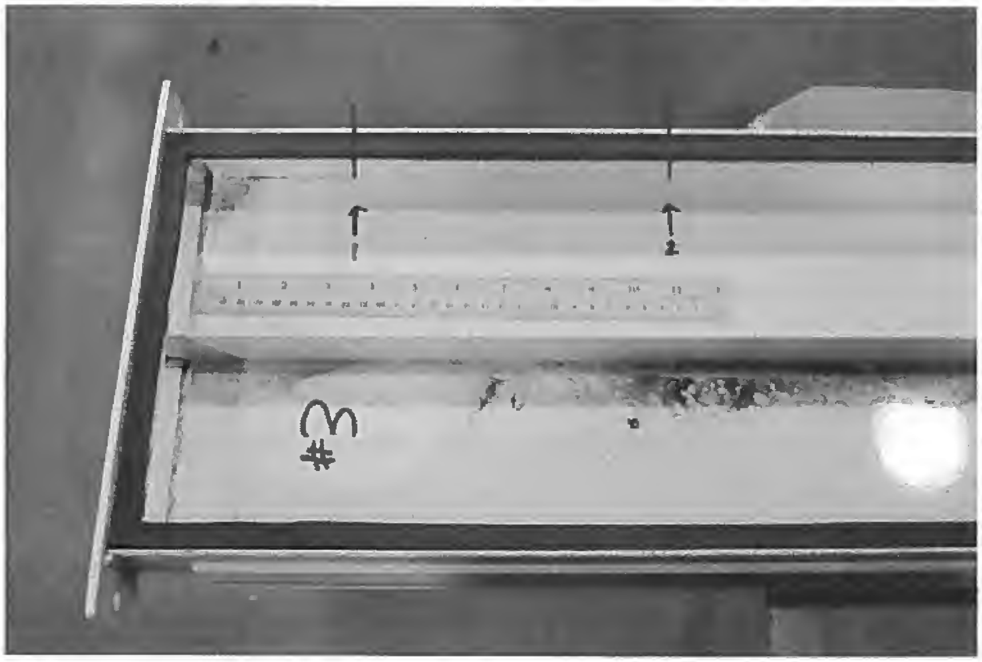


Figure 25: Sample #3: The cross-section locations for 3-1 and 3-2.

Figure 26: Sample #1: Mount 1-3. This location is away from the clip. Overall view of the mounted cross-section. The clip is attached to the lip location.

Figure 27: Sample #1: Mount 1-3. The clip is attached to the lip location.

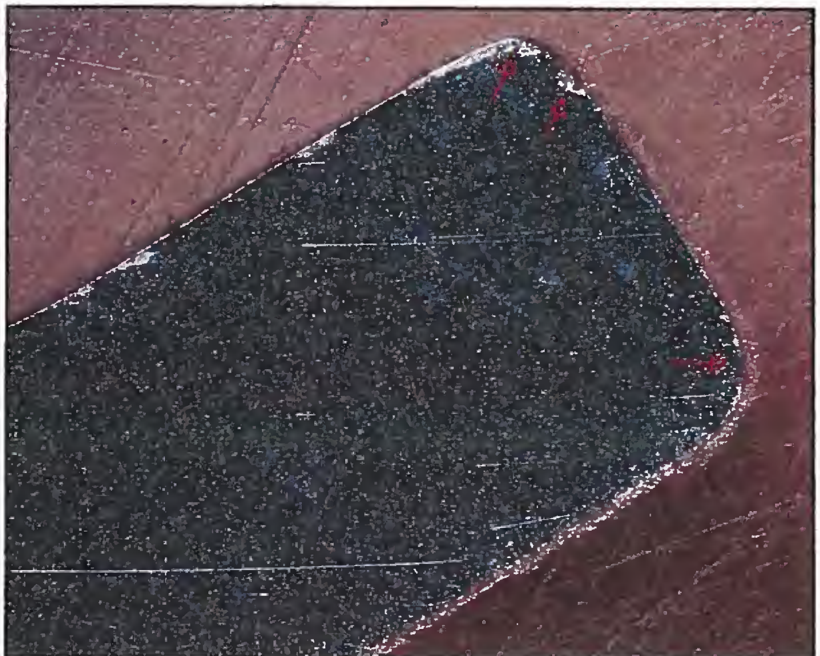


Figure 28: Sample #1: Mount 1-3. Lip area. Arrows point to areas with evidence of corrosion.

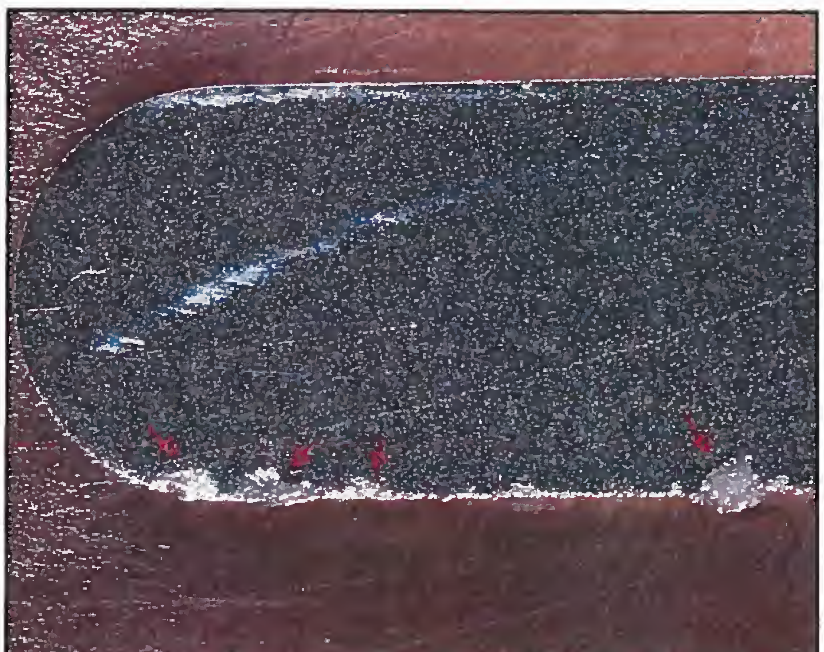


Figure 29: Sample #1: Mount 1-3. Tab opposite to the lip. Arrows point to areas with evidence of corrosion.

Mag. 4.2 : 1 ⊢200 mils⊣

Figure 30: Sample #1: Mount 1-1. This mount is through the wasted area where the clip was attached to the lip. Note completely consumed lip area with severe corrosion on adjacent surfaces.

Mag. 4.2 : 1 ⊢200 mils⊣

Figure 31: Sample #1: Mount 1-2. This area is next to the consumed lip location. Arrows point to corroded areas.

Figure 32: Sample #1: Mount 1-2. A higher magnification view of the lip location with corrosion.

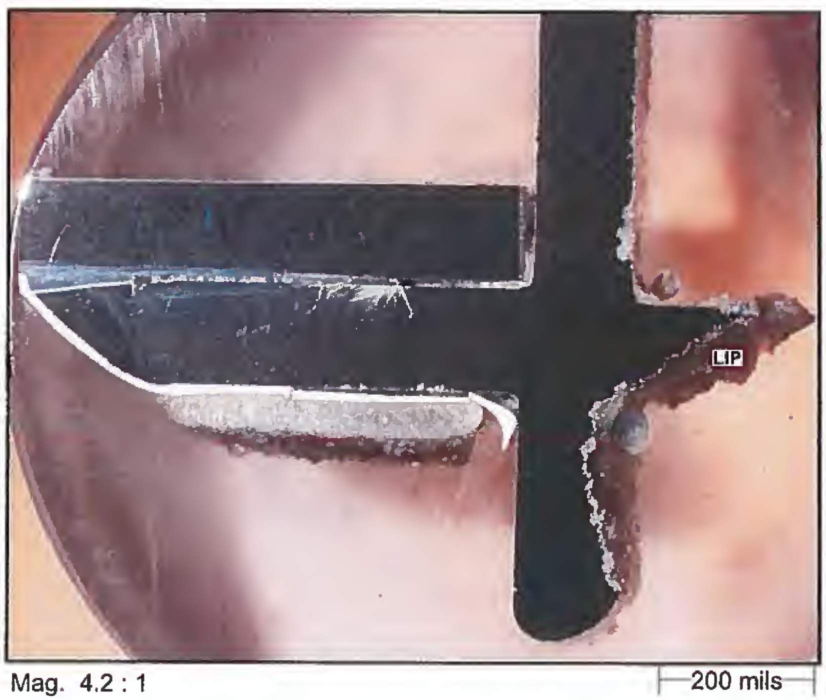
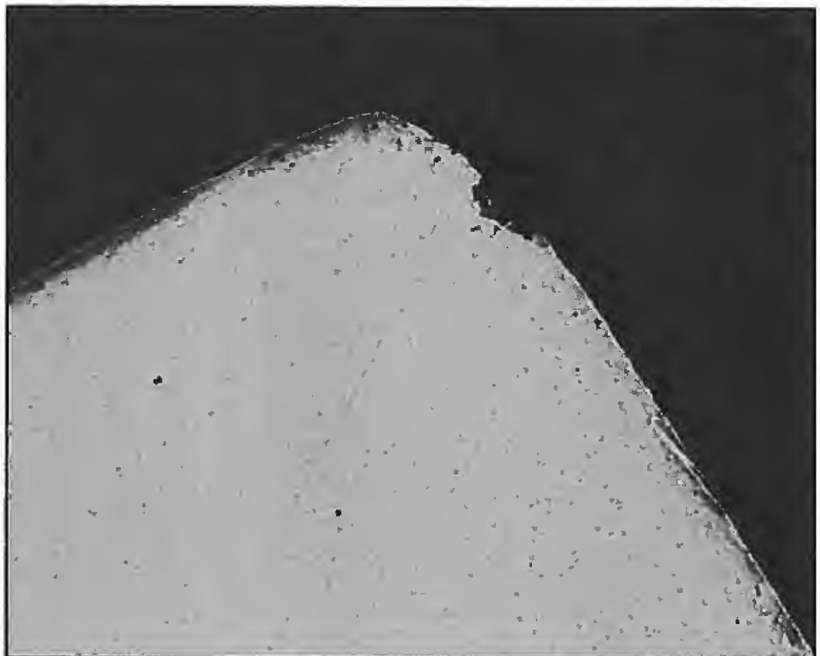


Figure 33: Sample #1: Mount 1-4. This mount is through another wasted area where the clip was attached to the lip. Note completely consumed lip area with severe corrosion on adjacent surfaces.

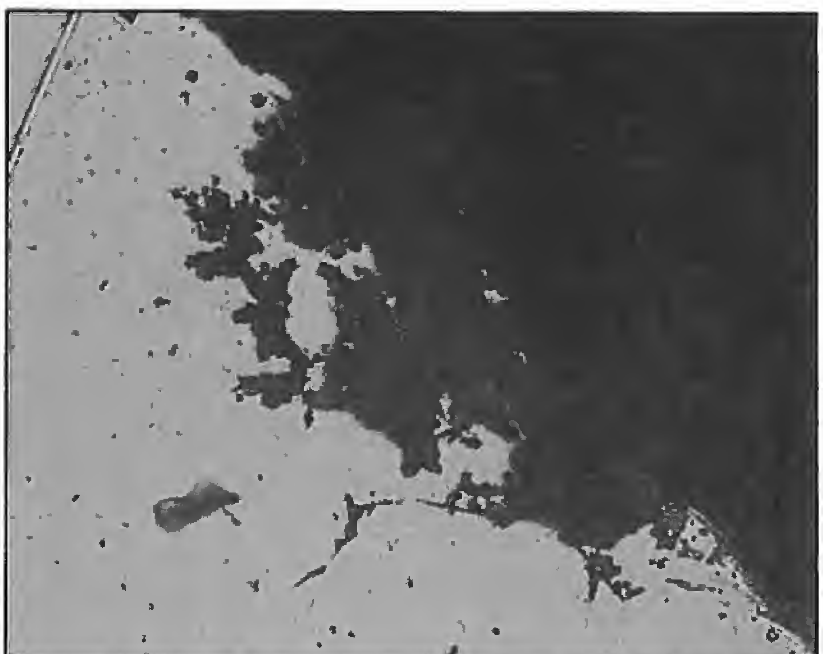
Figure 34: Sample #1: Mount 1-5. This area is next to the consumed lip location in mount 1-4. Arrows point to corroded areas.

Figure 35: Sample #1: Mount 1-5. A higher magnification view of the lip location with corrosion.



Mag. 64.5 : 1 20 mils

Figure 36: Sample #1:Mount 1-3; lip edge. Note some corrosion. Unetched.



Mag. 520 : 1 2 mils

Figure 37: Sample #1:Mount 1-3; lip edge. A higher magnification view. Note some corrosion. Unetched.

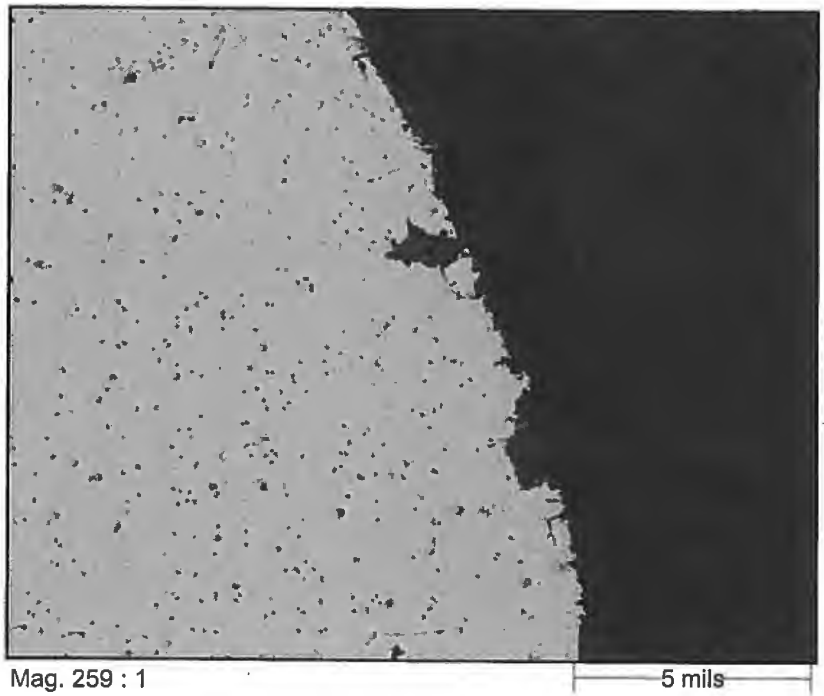


Figure 38: Sample #1:Mount 1-3; the other lip edge. Note shallow corrosion. Unetched.

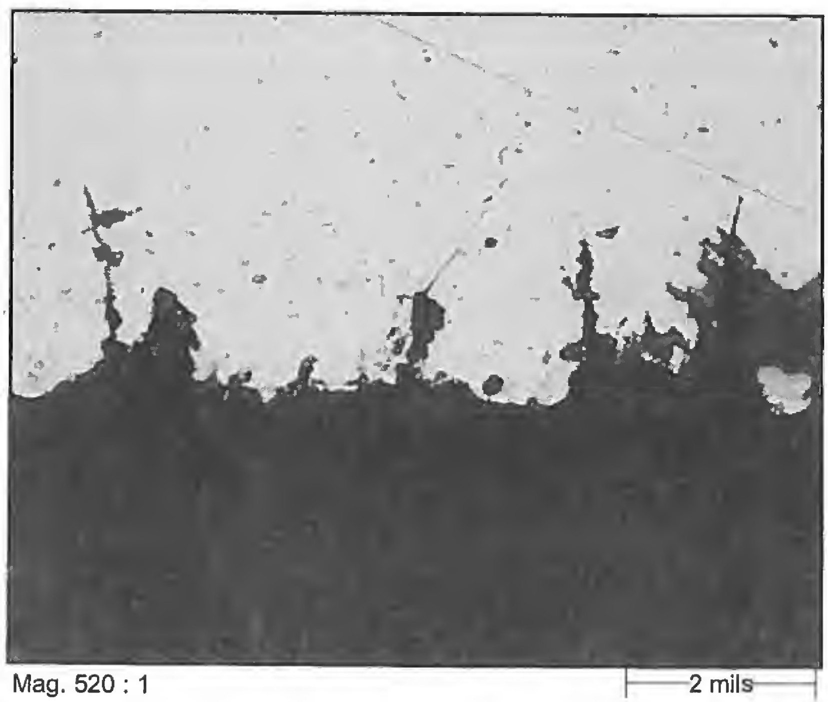


Figure 39: Sample #1:Mount 1-3; the tab area opposite to the lip area. Note some corrosion.

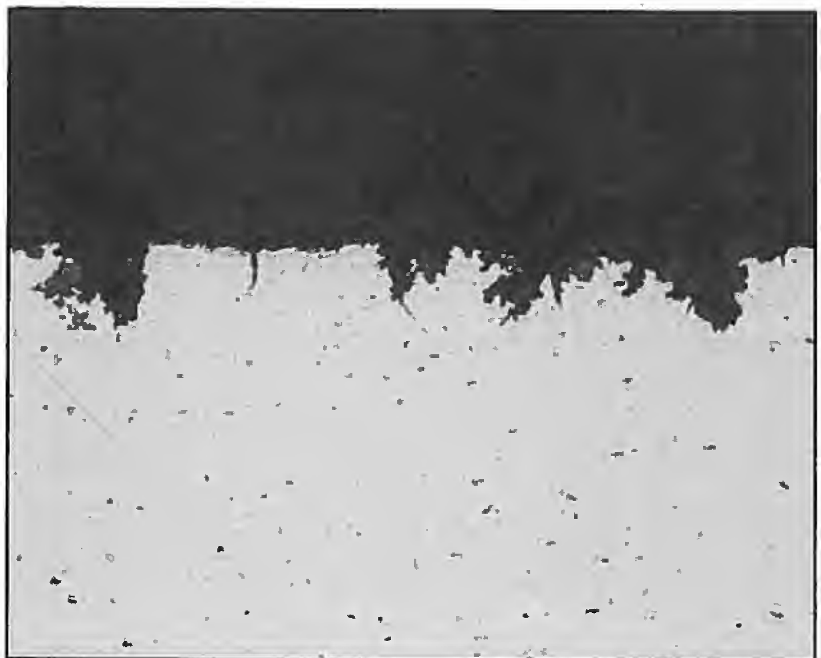


Figure 40: Sample #1:Mount 1-3; the tab area opposite to the lip area. Note initiation of corrosion in an intergranular mode progressing to pitting type. Unetched.

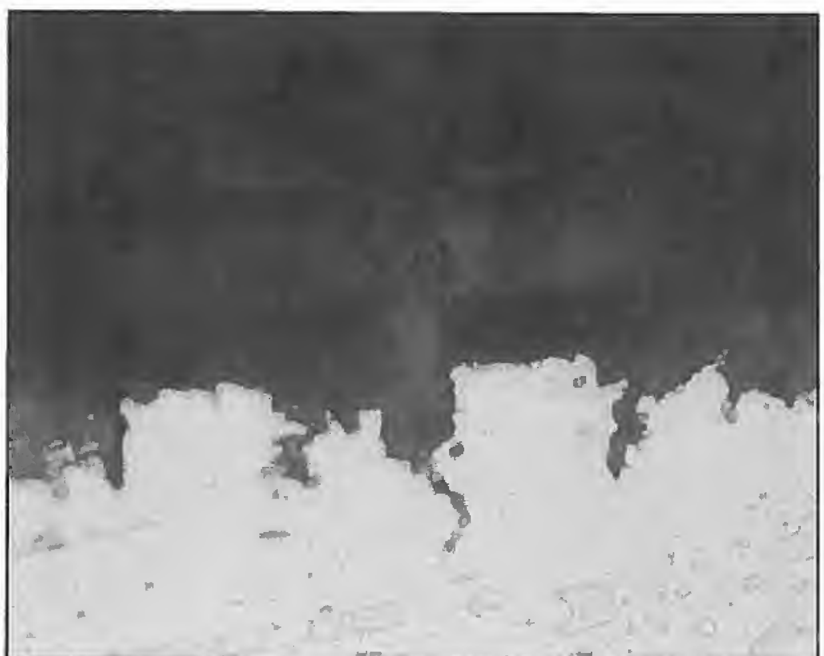


Figure 41: Sample #1: Mount 1-3; lip radius showing corrosion initiation.

Figure 42: Sample #1: Mount 1-2; note significant corrosion on the lip. Etched.

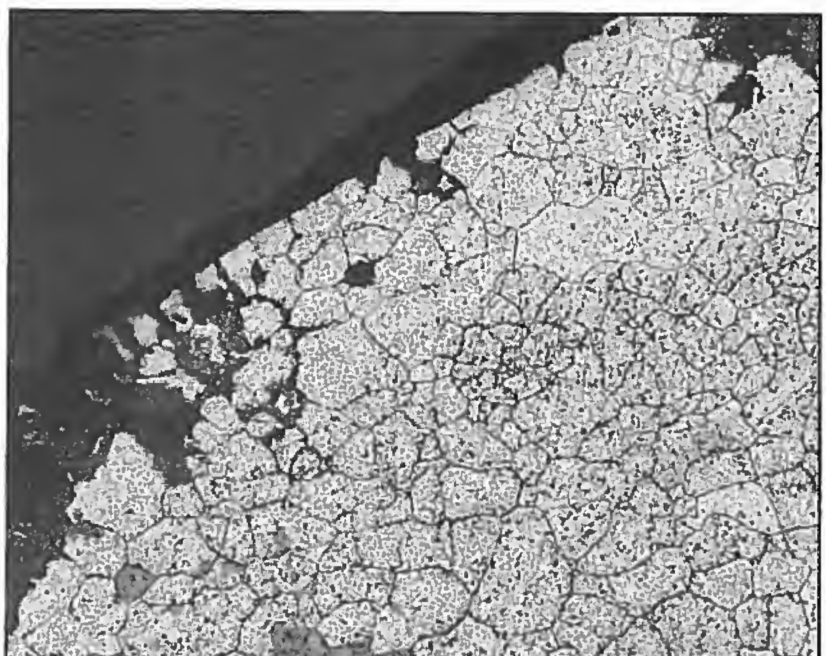


Figure 43: Sample #1: Mount 1-2; note significant corrosion on the lip. Etched.

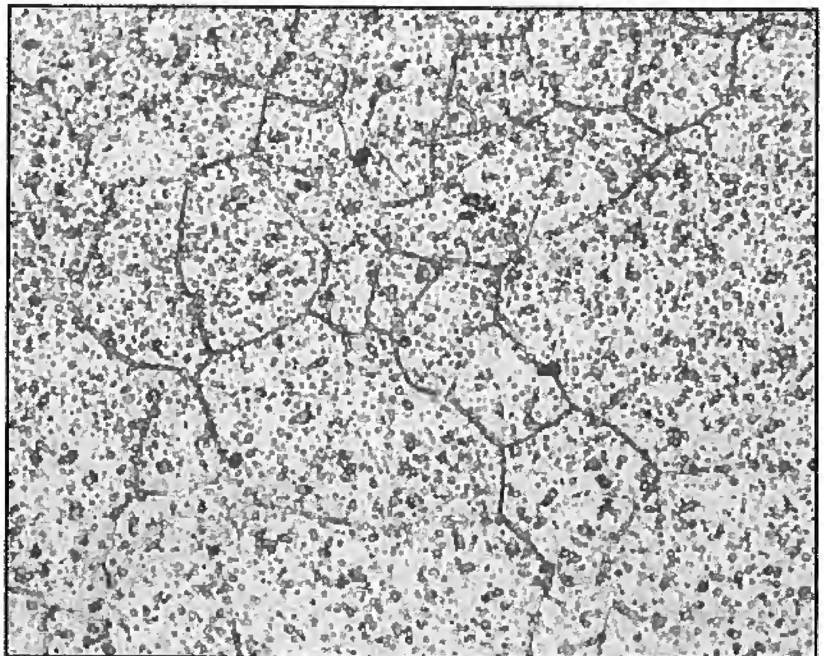


Figure 44: Sample #1: Mount 1-2; microstructure on the lip. Etched.

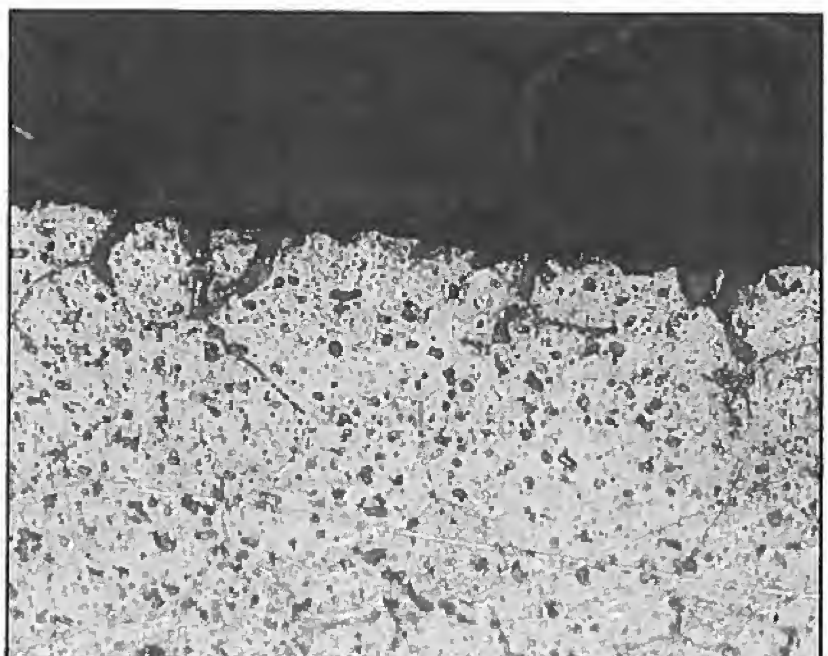


Figure 45: Sample #1: Mount 1-2; corrosion initiation in intergranular mode on lip radius . Etched.

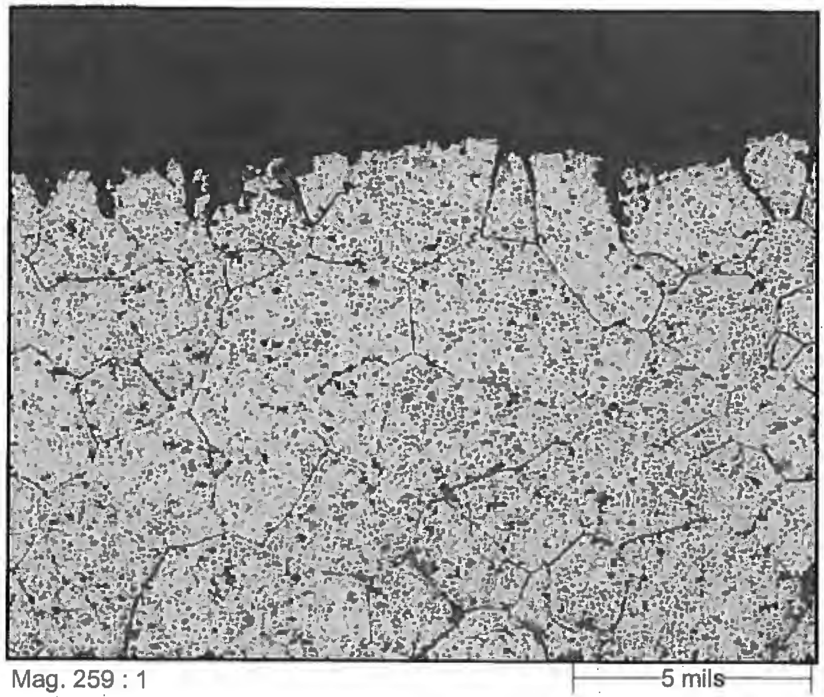


Figure 46: Sample #1: Mount 1-2; corrosion initiation on another surface. Etched.

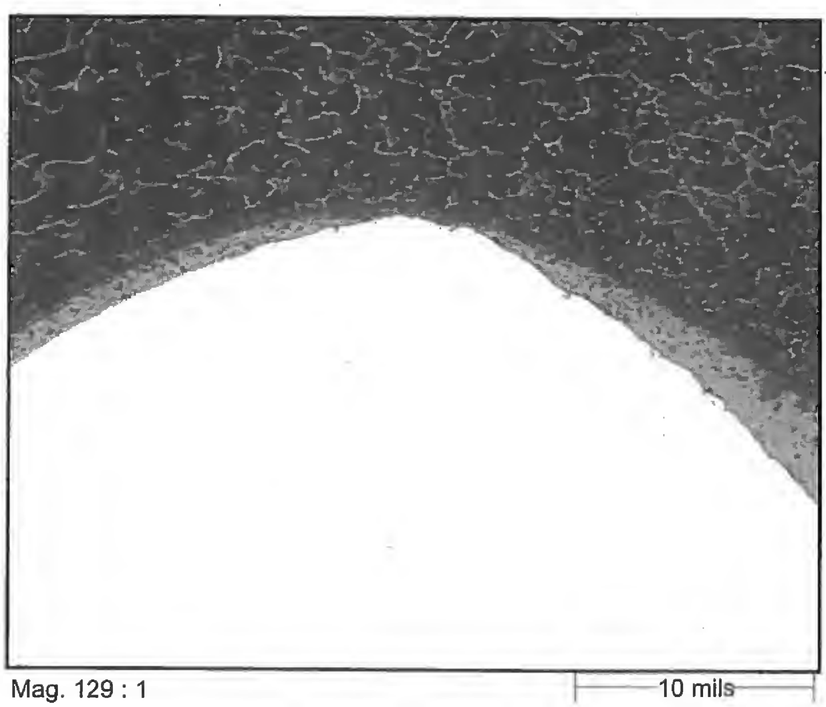


Figure 47: Sample #2: Mount 2-1; lip edge corner showing the thinner coating. Unetched.

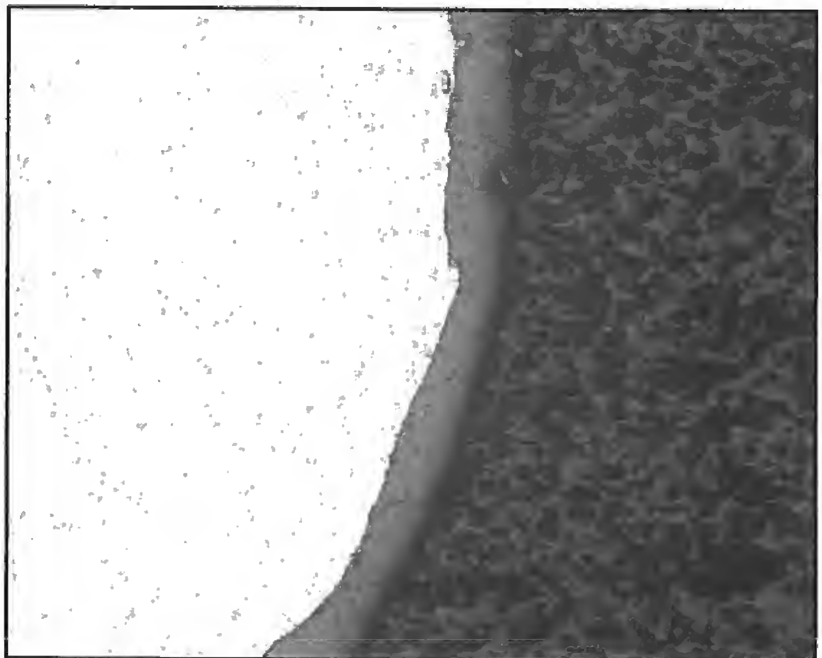


Figure 48: Sample #2: Mount 2-1; the other lip edge corner. Unetched.

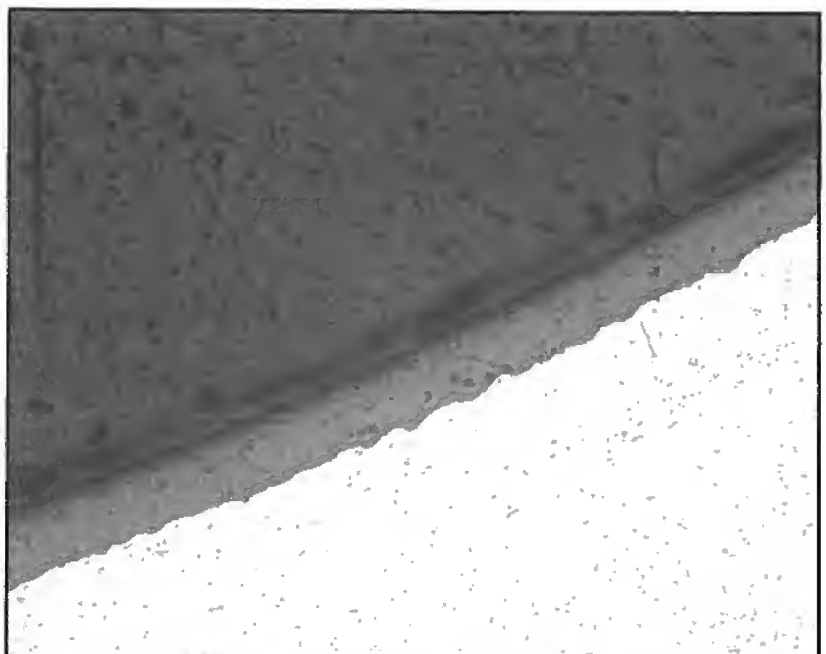


Figure 49: Mount 2-1: lip radius. Unetched.

Figure 50: Sample #2: Mount 2-1; lip radius. No contamination at the interface. Unetched.

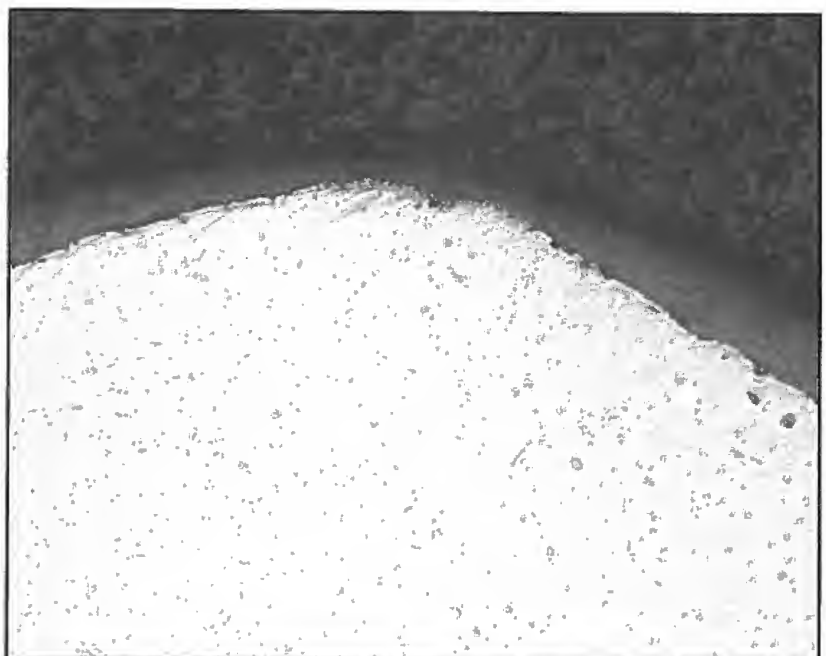


Figure 51: Sample #2: Mount 2-2; lip edge corner showing the thinner coating. Unetched.

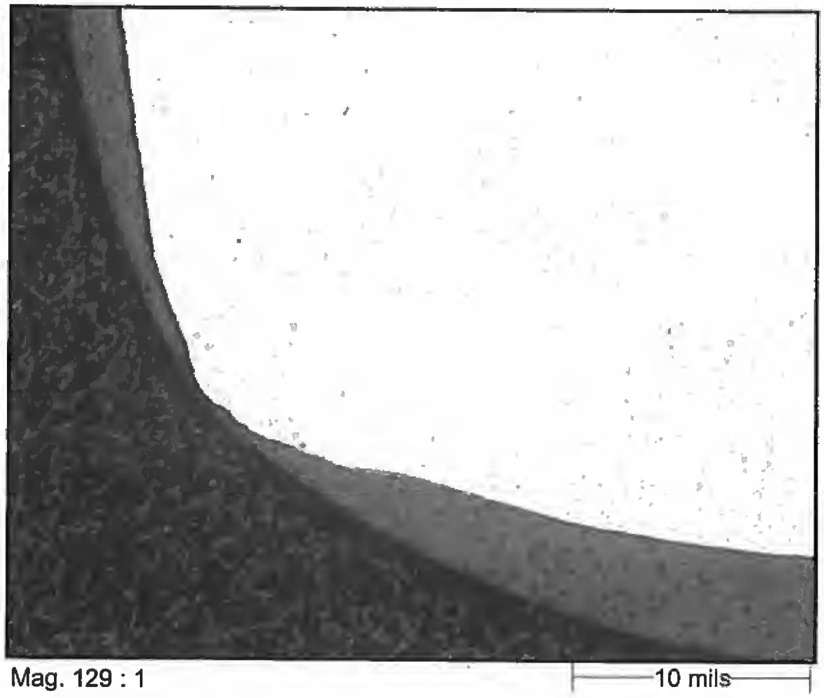


Figure 52: Sample #2: Mount 2-2; another corner away from the lip. Unetched.

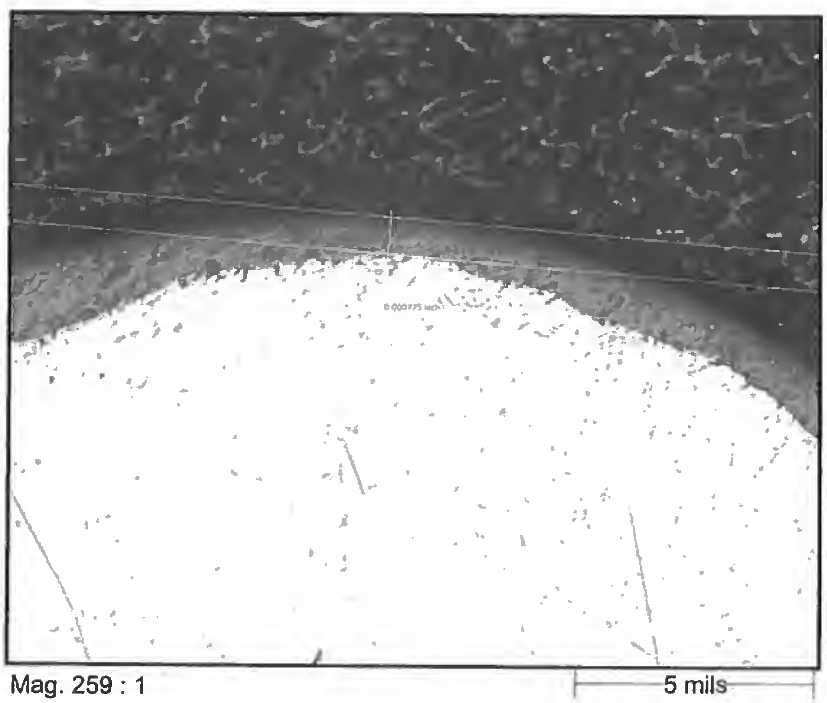
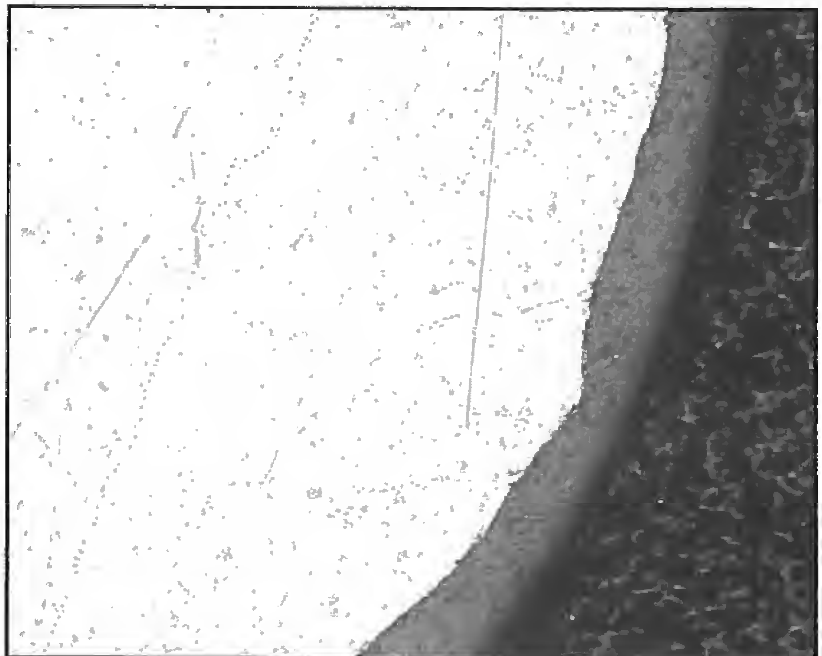
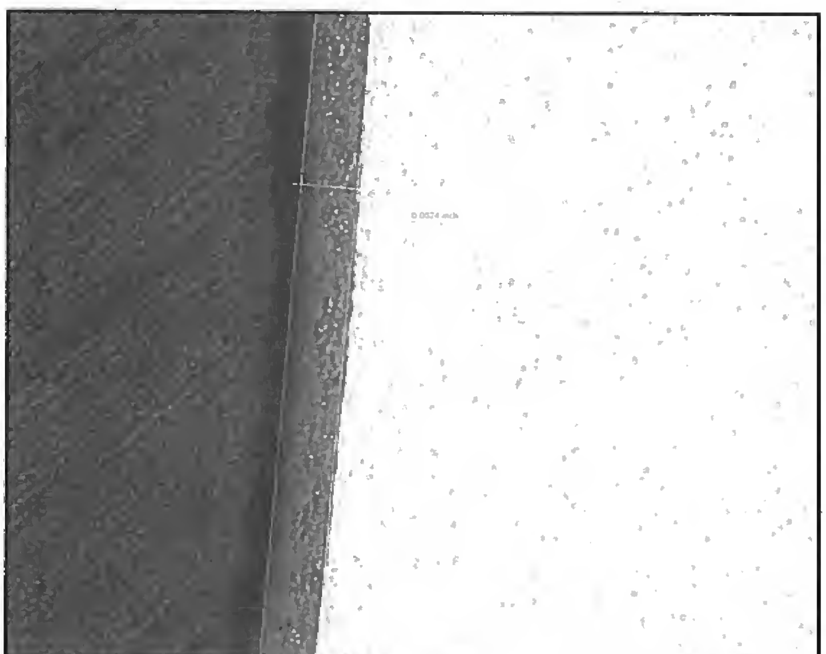


Figure 53: Sample #3: Mount 3-1; lip edge corner showing the thinner coating. Unetched.



Mag. 259 : 1 ⊢ 5 mils ⊣

Figure 54: Sample #3: Mount 3-1; the other lip edge corner. Unetched.



Mag. 129 : 1 ⊢ 10 mils ⊣

Figure 55: Sample #3: Mount 3-1; above the lip radius. Unetched.

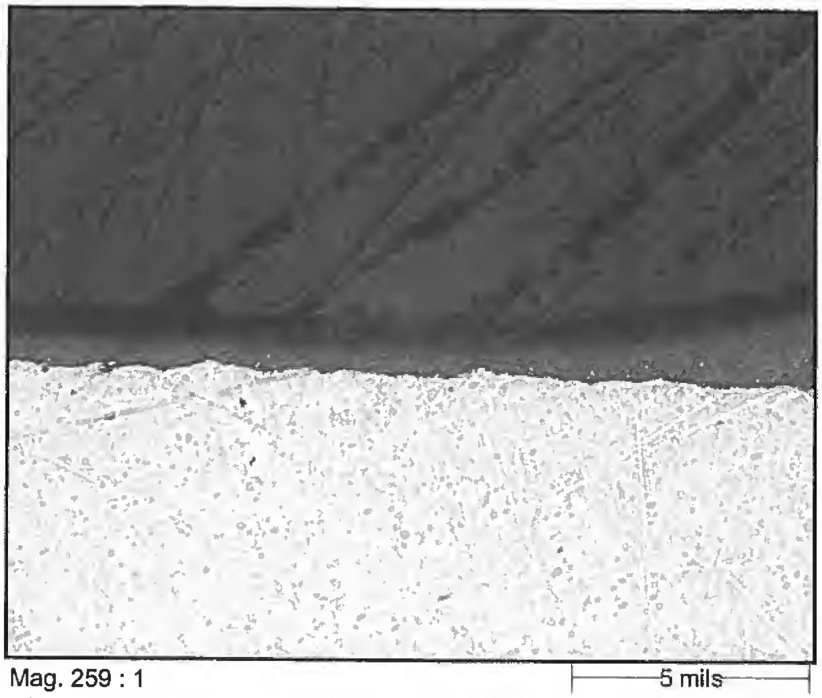


Figure 56: Sample #3: Mount 3-1; other leg of the radius. Note non-uniform coating distribution. Unetched.

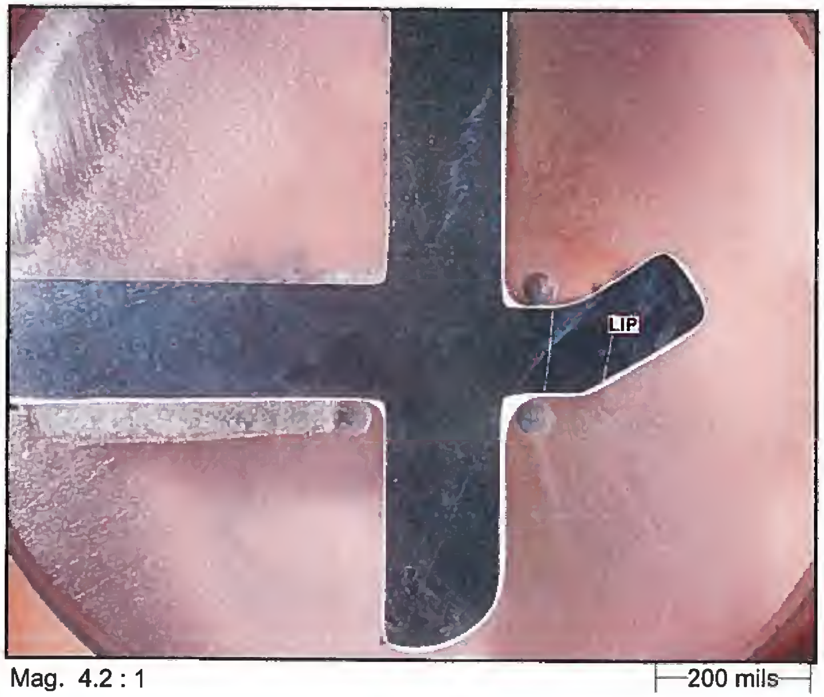


Figure 57: Sample #2: NuArt, new. Mount 2-2. An overall view of the mounted cross-section. The white surface is the coating.

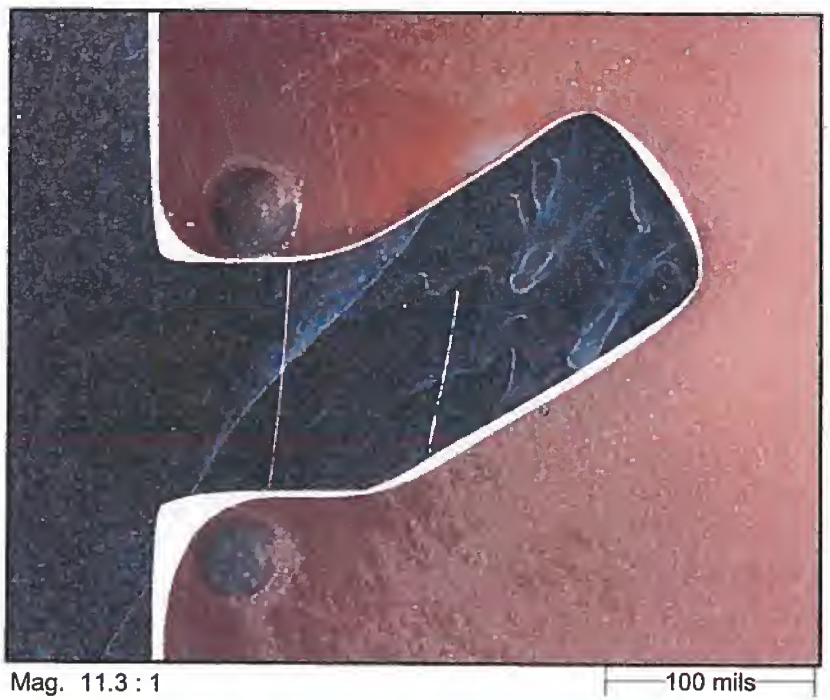


Figure 58: Sample #2: NuArt, new. Mount 2-2. A higher magnification view of the lip area.

Figure 59: Sample #2: NuArt, new. Mount 2-2. A higher magnification view of the lip area. Note thin coating at the edges/corners.

Figure 60: Sample #2: NuArt, new. Mount 2-2. A corner of the lip showed the coating thickness to be 0.0005".

Figure 61: Sample #2: NuArt, new. Mount 2-2. The other corner of the lip showed the coating thickness to be 0.001".

Figure 62: Sample #3: Schreader, new. Mount 3-2. An overall view of the mounted cross-section. The white surface is the coating.

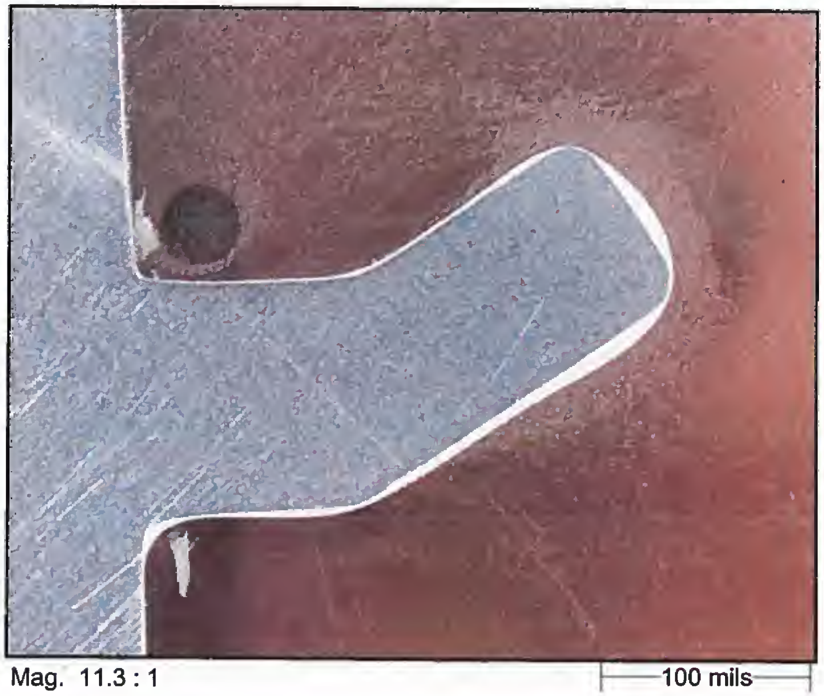


Figure 63: Sample #3: Mount 3-2. A close up view of the lip area.

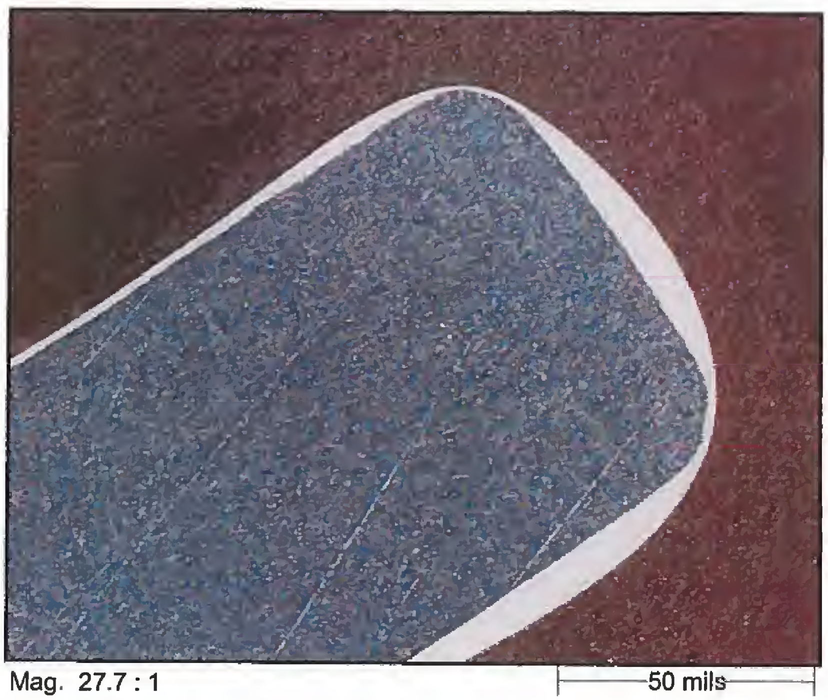


Figure 64: Sample #3: Schreader, new. Mount 3-2. A higher magnification view of the lip area. Note thin coating at the edges/corners.

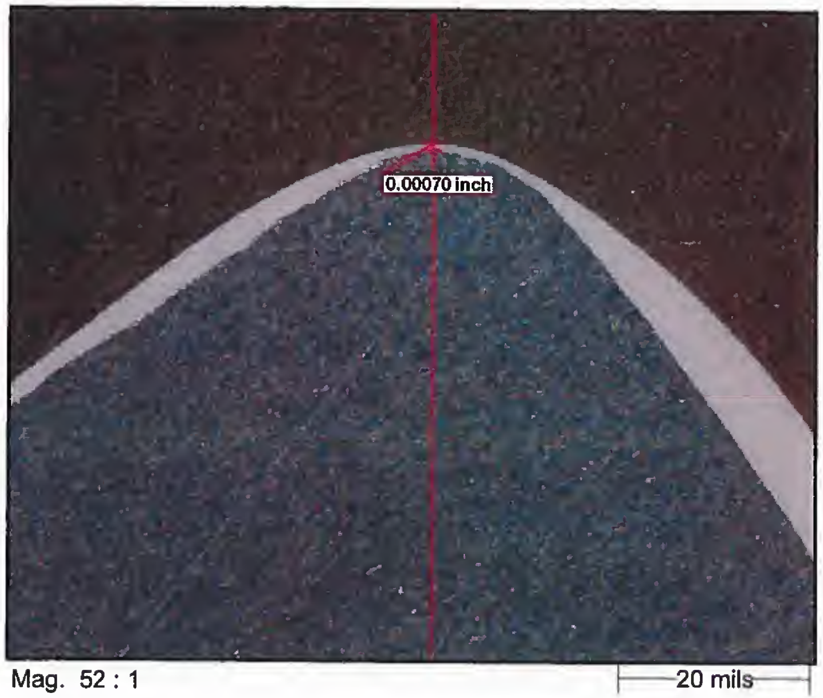


Figure 65: Sample #3: Schreader, new. Mount 3-2. A corner of the lip showed the coating thickness to be 0.0007".

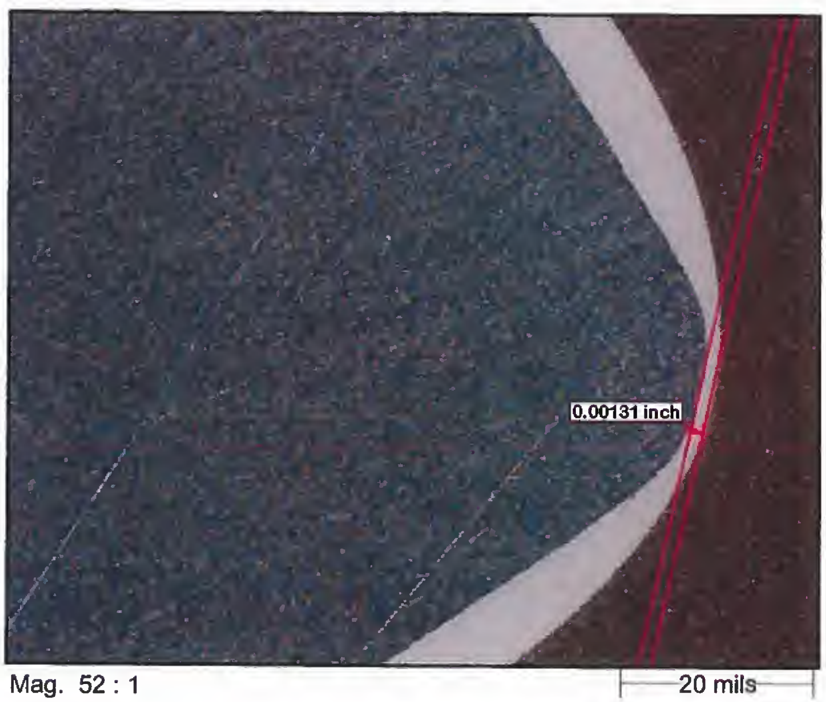


Figure 66: Sample #3: Schreader, new. Mount 3-2. The other corner of the lip showed the coating thickness to be 0.001".

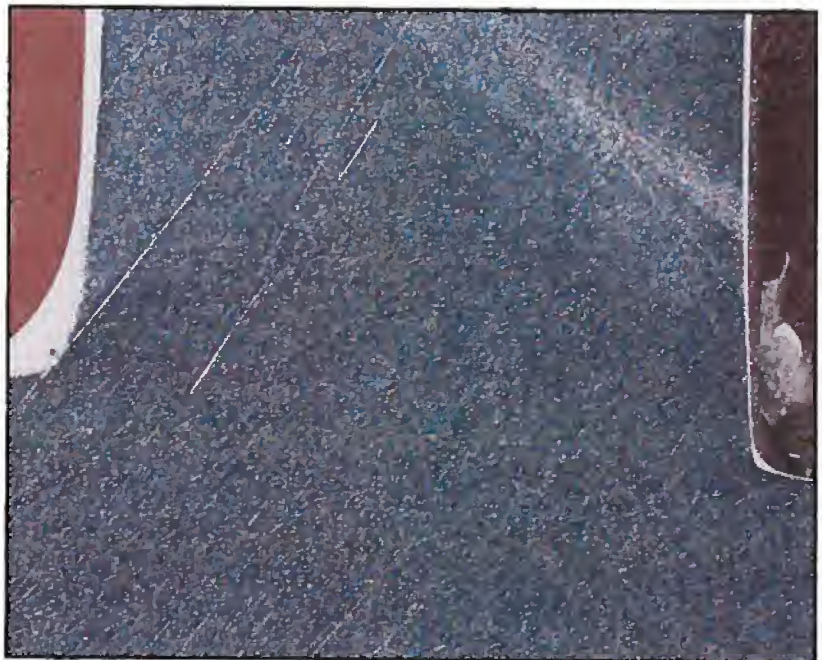
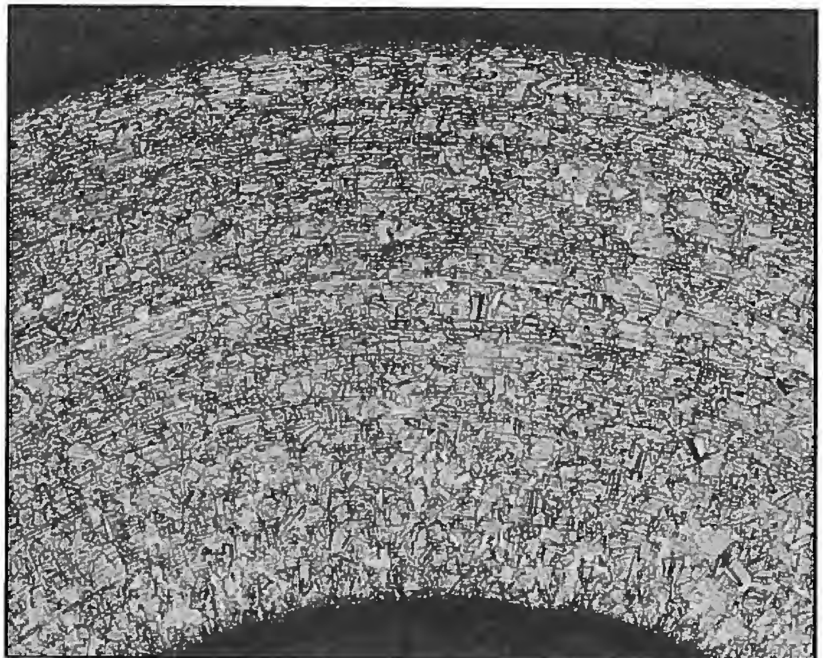


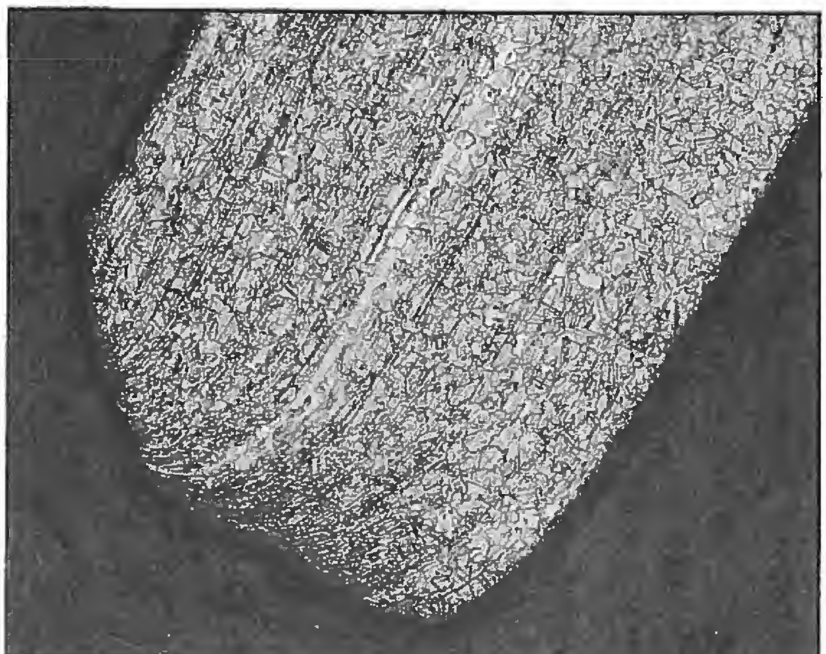
Figure 67: Sample #3: Schreader, new. Mount 3-2. An overall view of the mounted cross-section. Note the variation in coating thickness.

Figure 68: Sample #3: Schreader, new. Mount 3-2. Note the variation in coating thickness. This is the radius at the lip.



Mag. 64.5 : 1 20 mils

Figure 69: Failed clip: No corrosion noted at the ID of the bend. Etched.



Mag. 64.5 : 1 20 mils

Figure 70: Failed clip: No corrosion noted at the wireway contact corner. Etched.

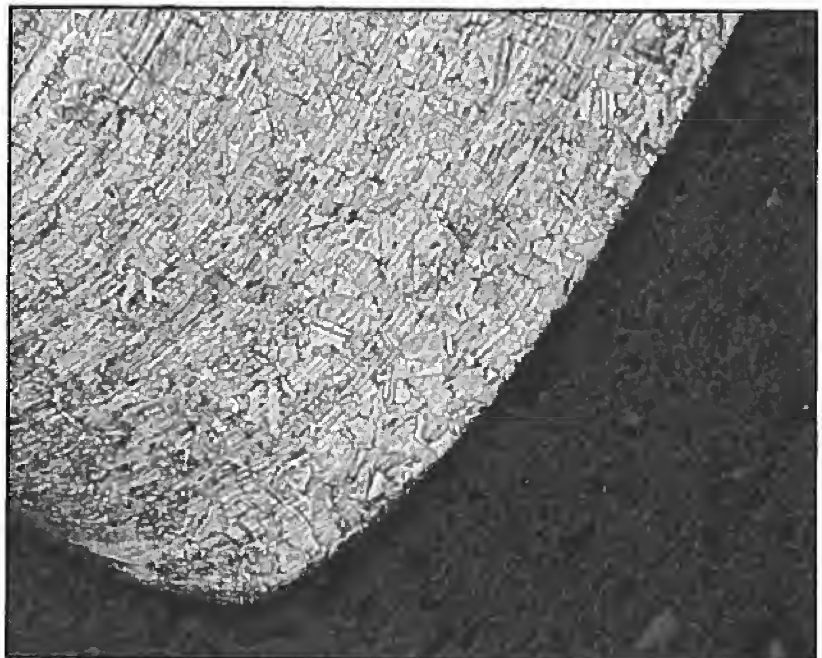


Figure 71: Failed clip: No corrosion noted at the wireway contact corner. A higher magnification view. Etched.

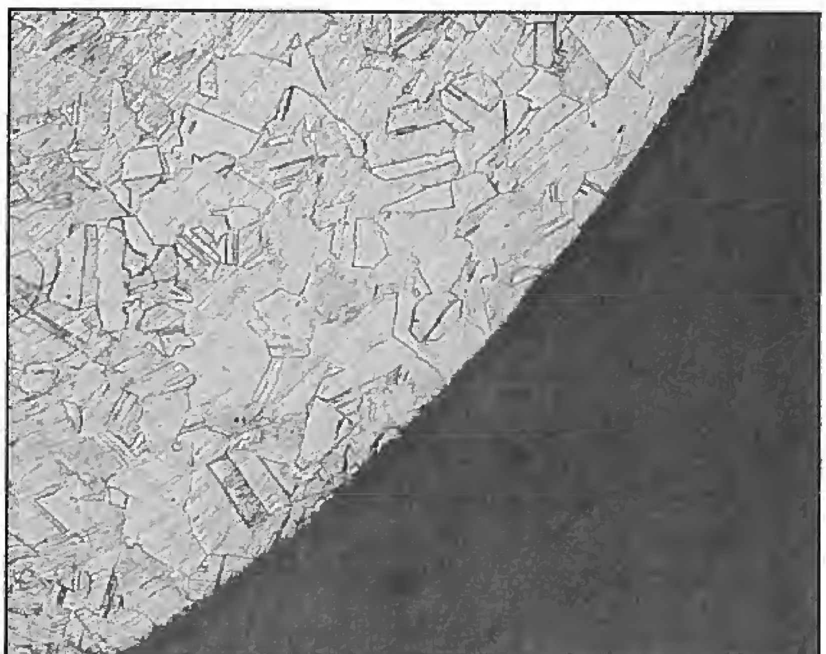


Figure 72: Failed clip: No corrosion noted at the wireway contact corner. A higher magnification view. Etched.

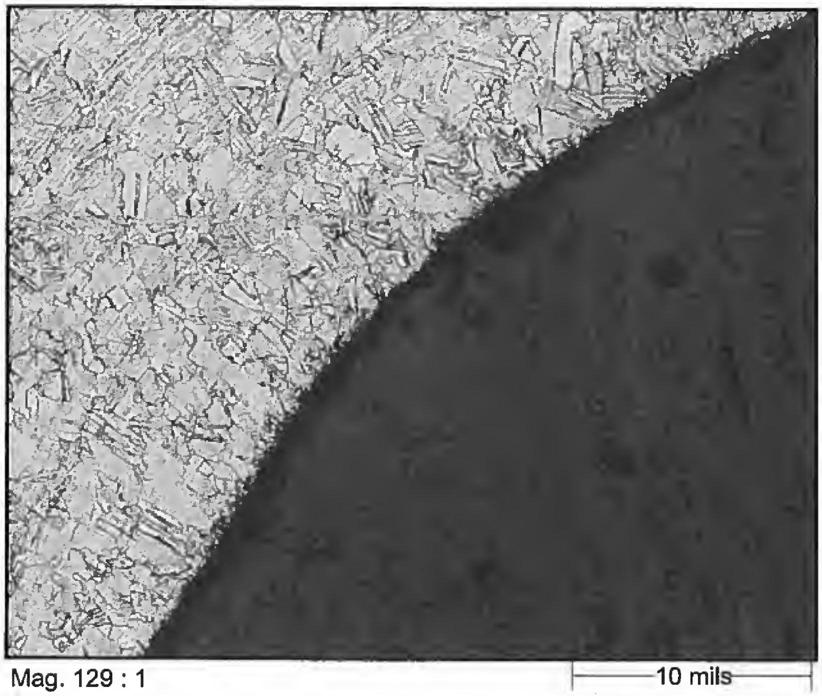


Figure 73: Failed clip: No corrosion noted at the ID of the bend. This area would be in contact with the wireway. Etched.

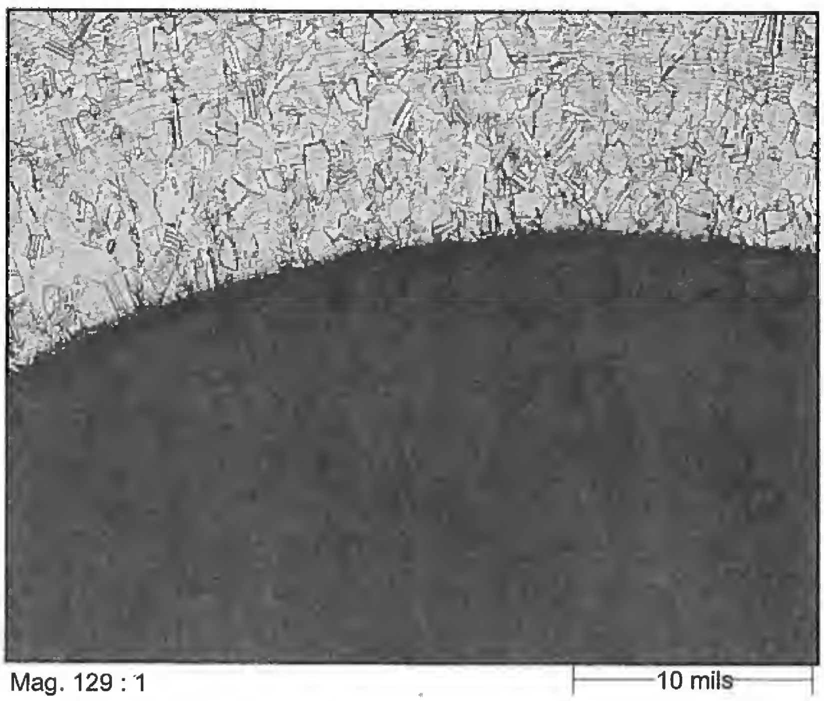


Figure 74: Failed clip: No corrosion noted at the ID of the bend. This area would be in contact with the wireway. A higher magnificication view. Etched.

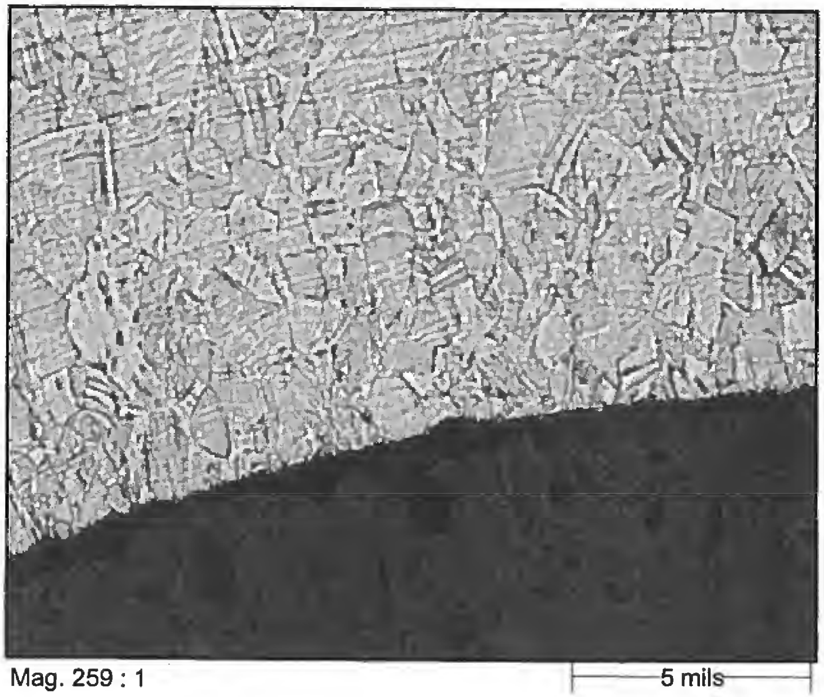


Figure 75: Failed clip: No corrosion noted at the ID of the bend. This area would be in contact with the wireway. A higher magnificication view. Etched.

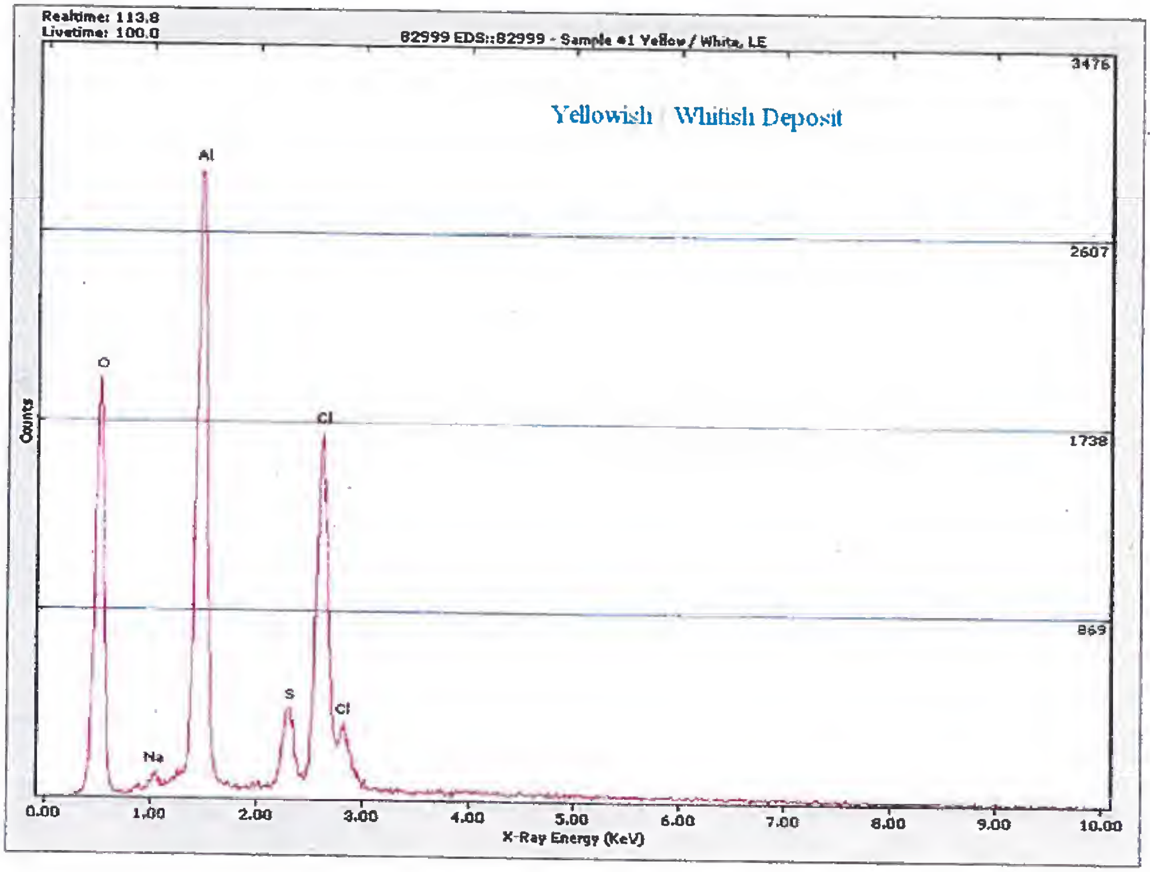


Figure 76: EDS spectrogram

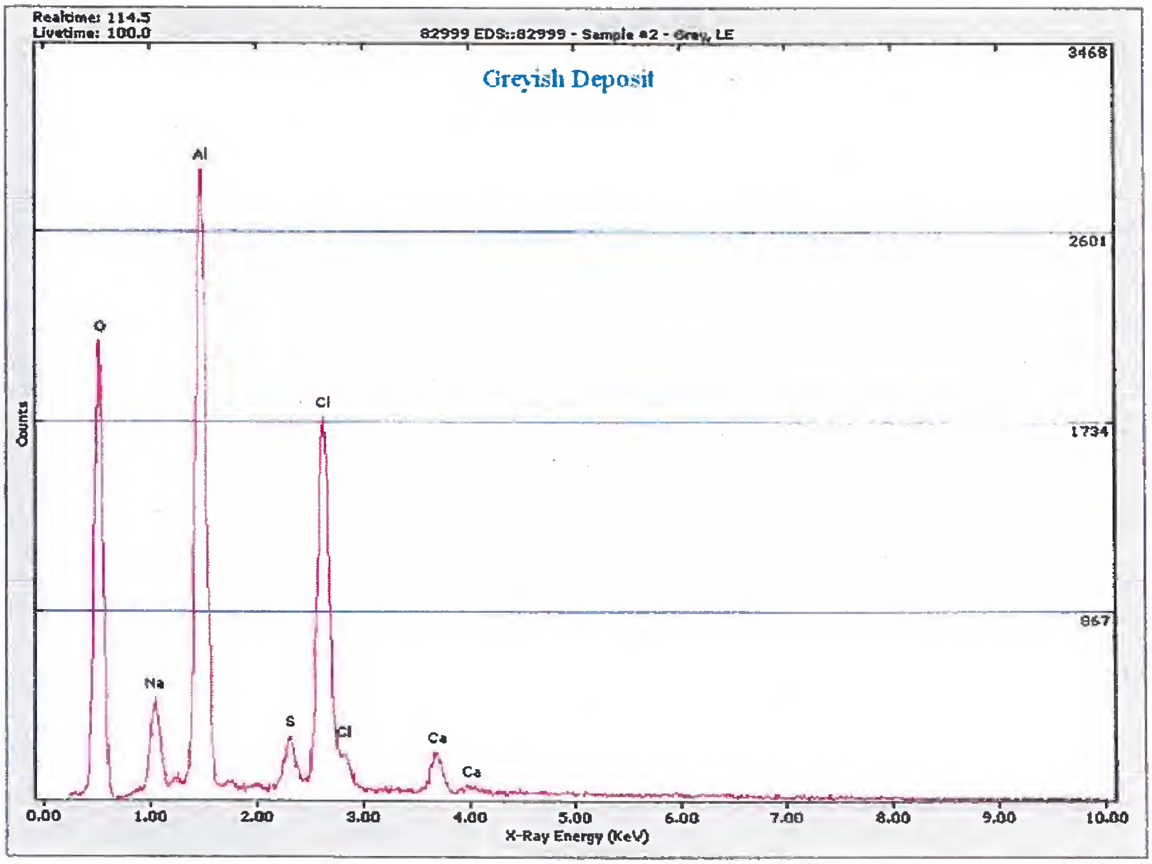


Figure 77: EDS spectrogram

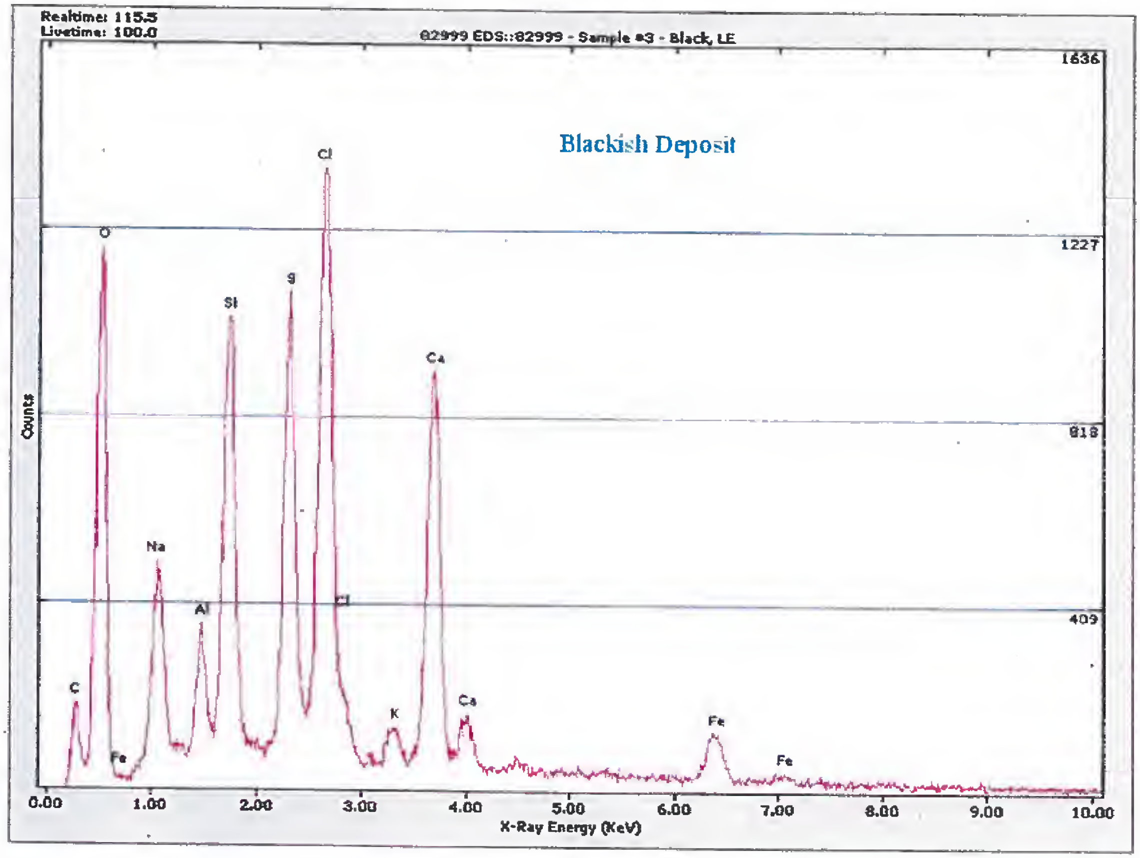


Figure 78: EDS spectrogram

Galvanic Series of Some
Commercial Metals and Alloys in Seawater

Noble or cathodic ↑

Platinum
Gold
Graphite
Titanium
Silver
Chlorimet 3 (62 Ni, 18 Cr, 18 Mo)
Hastelloy C (62 Ni, 17 Cr, 15 Mo)
18-8 Mo stainless steel (passive)
18-8 stainless steel (passive)
Chromium stainless steel 11-30% Cr (passive)
Inconel (passive) (80 Ni, 13 Cr, 7 Fe)
Nickel (passive)
Silver solder
Monel (70 Ni, 30 Cu)
Cupronickels (60-90 Cu, 40-10 Ni)
Bronzes (Cu-Sn)
Copper
Brasses (Cu-Zn)
Chlorimet 2 (66 Ni, 32 Mo, 1 Fe)
Hastelloy B (60 Ni, 30 Mo, 6 Fe, 1 Mn)
Inconel (active)
Nickel (active)
Tin
Lead
Lead-tin solders
18-8 Mo stainless steel (active)
18-8 stainless steel (active)
Ni-Resist (high Ni cast iron)
Chromium stainless steel, 13% Cr (active)
Cast iron
Steel or iron
2024 aluminum (4.5 Cu, 1.5 Mg, 0.6 Mn)
Cadmium
Commercially pure aluminum (1100)
Zinc
Magnesium and magnesium alloys

Active or anodic ↓

Figure 79: Courtesy of *Corrosion Engineering;* M. Fontana and N. Greene; McGRAW-HILL, Second Edition, 1978, pg. 32.

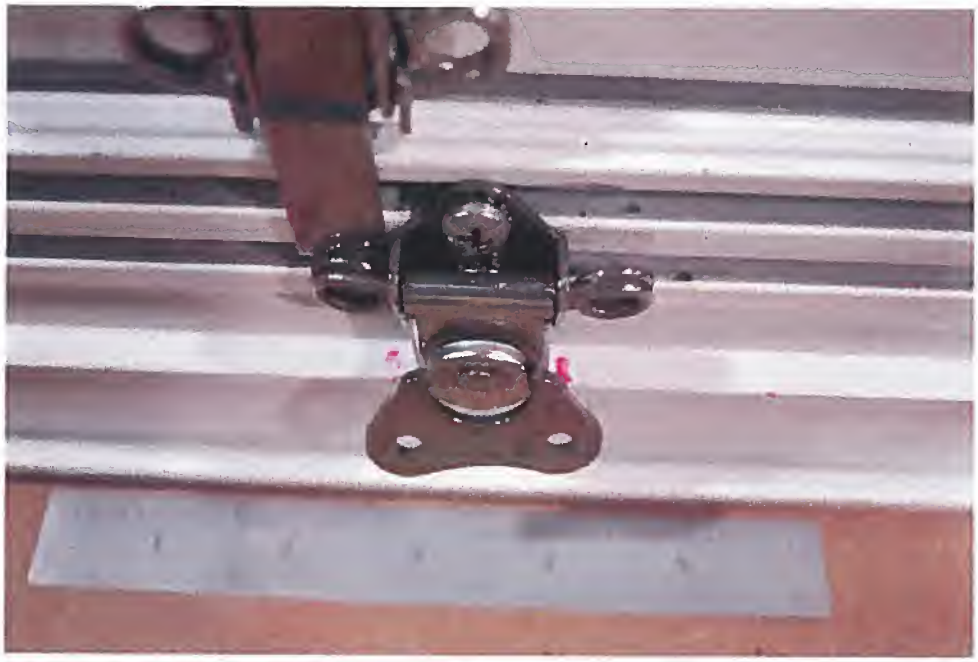


Figure 80: Sample #2 (NuArt): The new light fixture was attached to the new wireway. The pink lines are put on to show the area of clip attachment.

Figure 81: Sample #2 (NuArt): The same as in Figure 80 at an angled view showing attachment of a clip to the wireway lip.

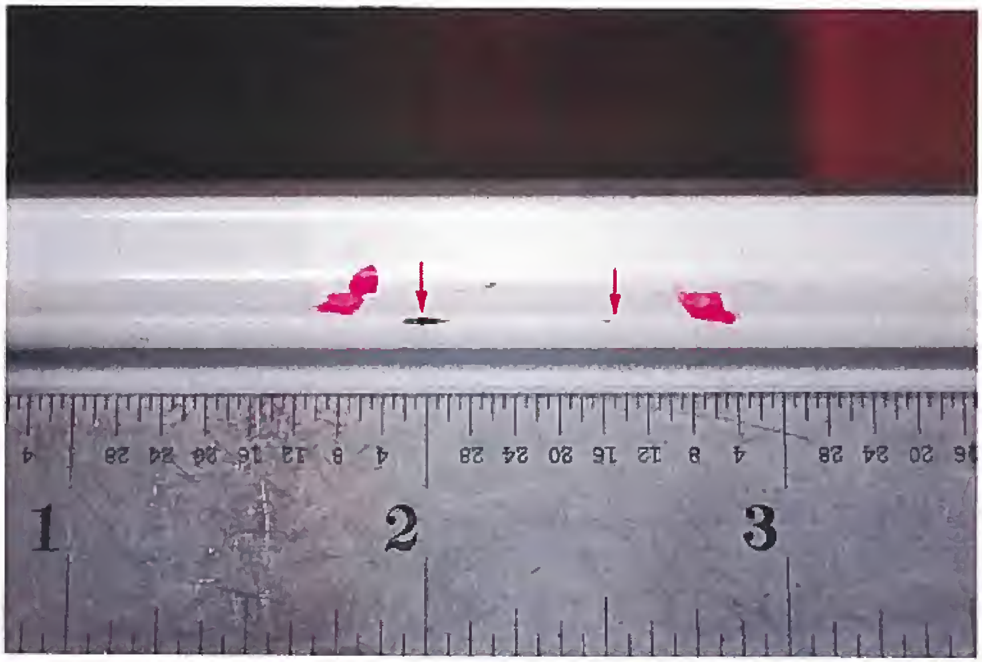


Figure 82: Sample #2 (NuArt): The wireway lip area after removal of the clip. Arrows point to the breached coating at the edge/corner. The coating was intact in this location before assembly of the clip.

Figure 83: Sample #2 (NuArt): The same area as in the previous photograph showing the coating damage, arrows, on the underside of the lip after removal of the clip.

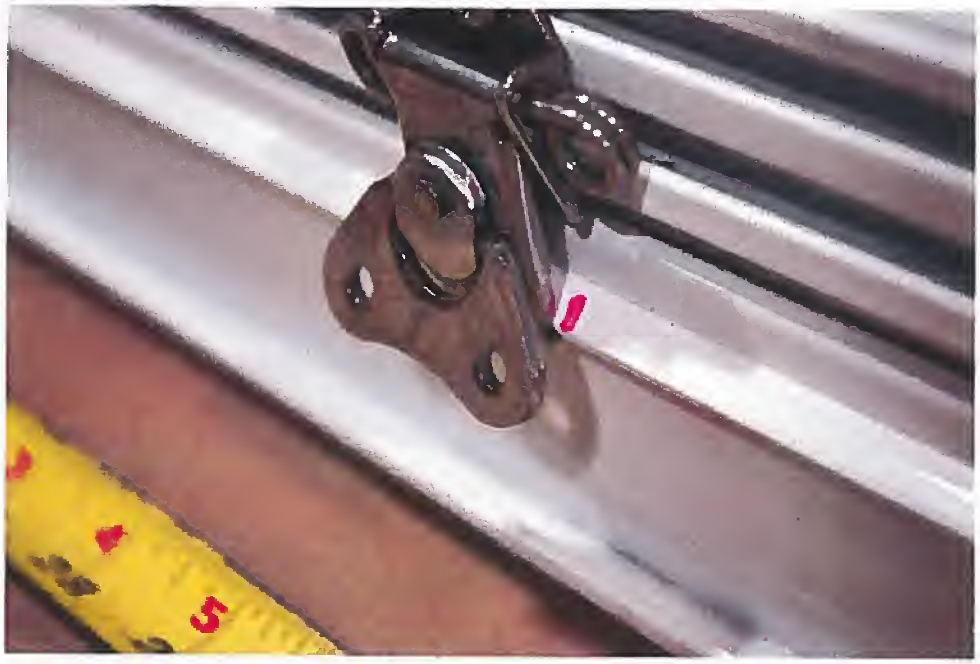


Figure 86: Sample #3 (Schreader): The same as in Figure 85 viewed from an angle to show the clip attachment to the lip area of the wireway.

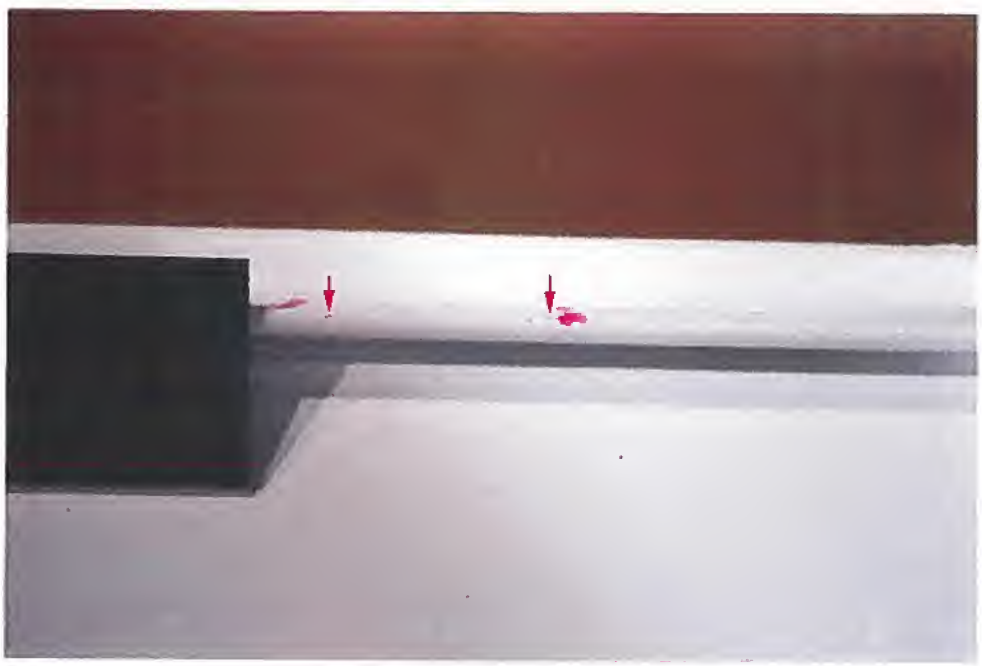


Figure 87: Sample #3 (Schreader): The same area as in the previous photograph after removal of the clip. The arrows point to the damaged coating at the lip edge.

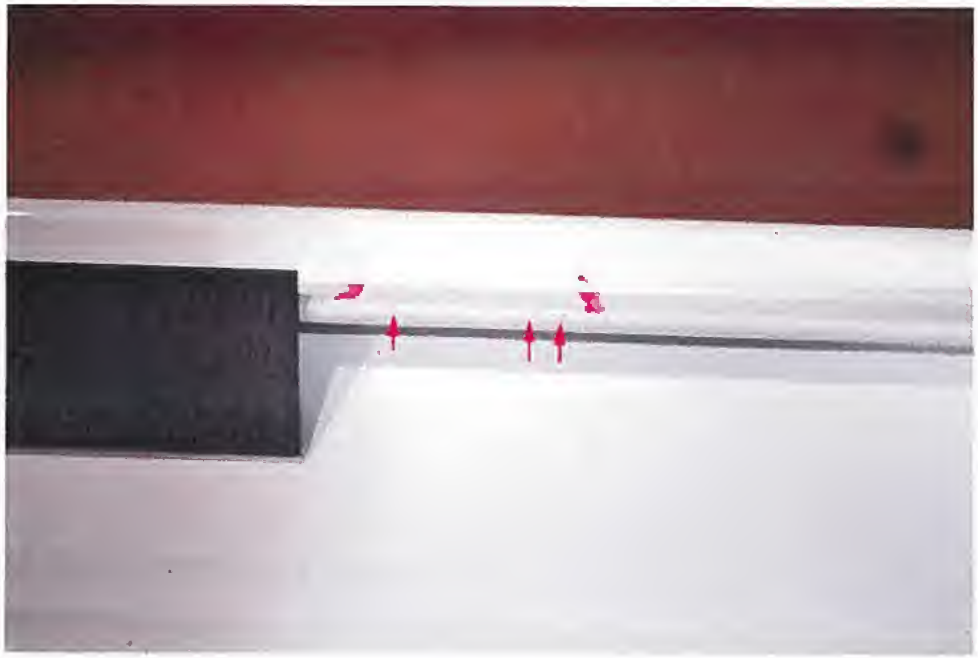


Figure 88: Sample #3 (Schreader): Another view of the area in Figure 87. Arrows point to coating damage.